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Advanced Wastewater Treatment Project to the NATO Committee on the Challenges of Modern Society. Volume I. The Report

Department of the Environment, London (England)

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NATO Committee on the Challenges of Modern Society, Brussels (Belgium)

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FINAL REPORT ON THE ADVANCED WASTEWATER TREATMENT PROJECT TO THE NATO COMMITTEE ON THE CHALLENGES OF MODERN SOCIETY.

THE NORTH ATLANTIC TREATY ORGANISATION

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WATER ENGINEERING DIRECTORATE

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This report does not finally evaluate Advanced Wastewater Treatment but does include much useful and wide-ranging work which will enable any further work on the matter to be better defined and better directed to the changed wastewater situation. The report further suggest there is now a more confident appreciation of the advantages of using oxygen in the activated sludge process that might be taken into consideration when its special features would be of benefit. Likewise the work on chemically aided settlement should enable the design of treatment plants with better and more predictable performance and better tuned to meet discharge requirements cost-effectively. It could also be used to uprate existing treatment plants and thereby defer heavy capital expenditures.

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CHAIRMAN'S FOREWORD

To the Chairman of the Committee on the Challenges of Modern Society,
Professor Ozdas

Sir,

1. The United Kingdom as Pilot Country is pleased to present this Final Report on the Advanced Wastewater Treatment Project after six years of most interesting work. At a meeting of our International Technical Group in London on 21 June 1978, representatives of our partners in the Study were in agreement with the scope, content and format of the Report and with the general conclusions drawn.

2. Like all good things, even this Study must end sometime. Clearly we have not finally evaluated Advanced Wastewater Treatment but we have done much useful and wide-ranging work. We think this will enable any further work to be better defined and better directed to the changed wastewater situation some six years after the initial study was set up.

3. We suggest there is now a more confident appreciation of the advantages of using oxygen in the activated sludge process and members might consider using it when its special features would benefit them.

4. Likewise the work on chemically aided settlement should enable the design of treatment plants with better and more predictable performance and better tuned to meet discharge requirements cost-effectively. It could also be used to uprate existing treatment plants and thereby defer heavy capital expenditure.

5. We proffer a draft resolution to effect these advantages.

6. At this last opportunity as Chairman of the International Group overseeing co-ordination I most sincerely thank our many helpers. There were too many for me to name individually and I must be content with their sponsors. Our first thanks must be to the Co-Pilot and Associate countries and their representatives, whose continued and unstinting help ensured the success we feel we have achieved. And we thank the Canadian Environmental Protection Service for lending us the Carbon Regenerating Furnace. I hope the happy co-operation achieved on this Study will continue long after the present work is completed for we can all help each other in some way.

7. Personally, I must thank the Department of the Environment for allowing me to undertake this exciting and rewarding work and for allocating the money needed for the United Kingdom's contribution. And I am indebted to those staff of my Research and Development Division who have so ably performed the onerous secretarial duties associated with this wide-ranging work.

ROY BEST

Chairman, International AWT Group
Department of the Environment
London SW1

June 1978

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1. Introduction

1.1 The Challenge

1.1.1. In recent times the world population has increased dramatically. In the 18th century it rose by 50% to 750 million. In the 19th century it doubled to 1500 million. In the first two-thirds of the 20th century it doubled again to 3,000 million. It is likely to increase further and lead to increased urbanisation with its attendant concentration of environmental problems.

1.1.2. Eminent men have dramatised the situation in attempts to stimulate action. Manlio Brosio — 4th Secretary General of NATO — said "It is the paradox of our times that the very progress achieved by man in the technological and social fields originally intended to improve his way of living now poses challenges to present and future generations." U Thant — then Secretary General of UN — said "It has become clear that we all live in one biosphere within which space and resources though vast are limited." Richard Nixon — then President of the USA — said "We are all advanced societies sharing the benefits and the gathering torments of a rapidly advancing industrial technology. The industrial nations share no challenge more urgent than that of bringing 20th century man and his environment to terms with one another — of making the world fit for man and helping man learn to remain in harmony with this rapidly changing world."

1.1.3. In brief: more people living on a fixed total resource will get less each and thus need to preserve and make better use of their shares.

1.1.4. The urgent challenge is certainly to discourage and hopefully to prevent proliferating persons from fouling their nests and destroying the very environment on which they rely for survival.

1.1.5. Improved wastewater treatment can make a significant contribution towards this and the NATO/CCMS AWT Project has helped considerably.

1.1.6. New readers may not all be aware that in 1969 the nations forming the North Atlantic Treaty Organisation (NATO) acting under Article 2 of the North Atlantic Treaty of twenty years earlier, formed the Committee on the Challenges of Modern Society (CCMS) to "examine how to improve, in every practical way, the exchange of views and experience among the allied countries in the tasks of creating a better environment for their societies, and to consider specific problems of the human environment with the deliberate objective of stimulating action by member governments".

1.1.7. CCMS has subsequently sponsored Studies on such matters as Advanced Health Care, Urban Transportation, Solar Energy, Geothermal Energy, Energy Conservation, Disaster Assistance and Road Safety.

1.1.8. The 'pilot country' method — claimed to be a new concept — is employed. A pilot country nominated by CCMS takes over responsibility for a Study, assisted where appropriate by one or more co-pilot countries; other countries may become associated. Each country carries out and pays for its own work under the Study.

1.1.9. A Final Report for each Study is prepared by the Pilot country and submitted to one of CCMS's twice-yearly Plenary meetings (attended by diplomatic and other representatives from each NATO nation.) Recommendations arising from Reports are submitted to the North Atlantic Council (NATO's 'Parliament') for national action.

1.2. General needs for wastewater treatment

1.2.1. Most nations have their own particular needs for wastewater treatment. These needs are influenced by naturally occurring environmental conditions such as climate, location and topography, water resources and natural drainage. They are also influenced by created environmental conditions such as domestic and industrial development patterns, planned land and other resource use and national policies generally. Then — importantly — they are controlled by more personalised considerations such as acceptable public health risk at commensurate cost, desirable living standards and what the people are prepared to pay for various levels of amenity.

1.2.2. But a continually and progressively developing world with changing conditions dictates that logically the need to meet those conditions should also develop similarly. This is particularly true for wastewater treatment where the needs of advancing civilisation are themselves always advancing. Increasing pressures for improvement of this treatment provide a common thread throughout the developing countries.

1.2.3. For example, even in the United Kingdom with its already highly developed water supply and drainage services there is an urgent need for improvement. About 97% of United Kingdom households already have a good mains water supply. About 95% of households have effective main drainage, and wastewater disposal mostly with secondary treatment. But emerging needs from increased environmental awareness indicate that higher standards may need to be met soon.

1.2.4. Section 13.4 of the Appendices describes very briefly the general situation in some other member countries.

1.2.5. The problem can be summarised generally that we need more capacity for treating increased flows of more complex wastewater more reliably and under automated control to a wider range of (including higher) standards for both effluent and sludge. These end-products must then continue to be disposed of without harm to health or damage to the environment and at a cost acceptable to the public at large.

1.2.6. In most areas populations are still increasing and the per capita consumption of water is still increasing. This means more water is used and in consequence the flow of wastewater for treatment is increasing noticeably. Improved urban drainage adds to this, particularly when fewer storm overflows are incorporated and natural soakage is used less.

1.2.7. The increased individual usage could lead to more but weaker sewage, but this dilution is offset by more sophisticated eating habits and generally increasing living standards and hence the discharge of more polluting matter. Thus in some cases the wastewater may be stronger.

1.2.8. Similarly industry continues to develop and some use more water, for example to meet higher hygiene requirements. Increased re-use within industry may have reduced this increase but is unlikely to eliminate it. The advent of many higher technologies involving new materials and more sophisticated processes, and the tendency sometimes to reduce disposal within the factory curtilage, has led to increased discharges from many industries. The use of more complex materials has usually led to stronger wastewater often more difficult to treat for safe discharge to the environment.

1.2.9. With more and larger abstractions for drinking water from the lower reaches of rivers, and shorter distances between these and effluent discharges, there is an increasing re-use of water used already — sometimes several times previously. This suggests a need for higher standards for the wastewater effluents discharged to abstraction rivers in particular, and certainly an urgent need to relate those standards to the natural purification capability of the receiving water between the discharge and the abstraction. Thus a range of discharge standards may need to be met.

1.2.10. With constantly improving analytical and monitoring techniques we can be more precisely aware of the pollutants in waters. Whilst we can in consequence know with more confidence how much of what we already know to be present must be dealt with and where, the new diagnoses can also reveal the presence of substances previously unsuspected and which may be hazardous.

1.2.11. Coupled with a greatly increased public awareness of the possible health and other hazards from disposal of wastewater to natural waters — and land — there is an obvious need for more embracing, more stringent and more flexible discharge requirements. Not only must these deal adequately with new materials which may not yet be completely evaluated, they must also cover older materials previously accepted without demur but now regarded as possible hazards.

1.2.12. The new appraisal leads to a new conceptual approach to effluent and sludge standards. There is a need arising to replace the present generally inflexible standards with a range of standards matched to the requirements of the separate receiving media. The past requirement of limits only on suspended solids — to prevent deposition of objectionable solids in rivers and other receiving waters — and on oxygen demand (and possibly ammonia) — to prevent adverse effects on fish and plants in those waters — are likely to be much extended. And most importantly, this leads to the need for a new approach to the design of the related treatment facility, for a reliably and more precisly controllable treatment process providing one or more standards of effluent and sludge from within a wide range. This is a significant departure from past and present practice.

1.2.13. Summarising the above requirements suggests that future wastewater treatment should have:

a. Precise and consistent performance in determined conditions
b. Reliable operation and control — desirably highly automated
c. Wide range of removal capabilities for a wide range of substances
d. Ability to match treatment given to load imposed including transient peak and shock loads; and seasonal and other variations
g. Standardised and scientifically based hydraulic capacity, pollutant-removal capability, and ground structural design
f. Planned life to match the likely need, to avoid creating a public-health monument for posterity

g. Designs incorporating modern materials, systems building techniques, modular dimensions and standardised units and equipment

h. Low external power/energy requirement with highly cost-effective design, construction, operation, and maintenance

i. Freedom from nuisance, an attractive appearance and aesthetically acceptable. It should use little land and provide the good working conditions demanded by present day Industry

1.2.14. The traditional physical/biological treatment plants which have served so well for so long are now thought to be near their limits of viable development in their present mode and are increasingly being overtaken by the need to meet more stringent discharge requirements.

1.2.15. The delightfully cheap, simple and mainly self-energised chain of preliminary, primary, secondary, and optionally tertiary treatment stages, relying mainly on gravity and biological oxidation with available organisms, gives a few but specific and limited ranges of effluent quality depending mainly on the stages used. Whilst performance can be regulated in some measure by subtleties of design, construction, and operation, there is little fine control over either effluent or sludge quality.

1.2.16. With few significant changes in process concept during the last 100 years and with effluent discharge standards in the United Kingdom largely unchanged since the Royal Commission recommendations about 60 years ago, the modern world could justifiably feel that something more up-to-date — and hopefully better — is long overdue. Hence the present evaluation of rarely used operational or novel processes which we have called Advance Wastewater Treatment.

2. Aims and scope of the study

2.1 Terms of Reference

2.1.1. CCMS paper AC/274-D/25 of 19 May 1972 nominated the United Kingdom as Pilot Country; and the United States, France and the Federal Republic of Germany as Co-Pilots for the Advanced Wastewater Treatment (AWT) Study. Particular attention was to be paid to:

a. Physical-chemical processes including clarification, carbon adsorption and associated sludge treatment;

b. Direct oxygen application to achieve improved efficiency in biological processes.

2.1.2. Studies on physical-chemical processes would be carried out in the United Kingdom supported by information and assistance from the United States. Parallel studies on oxygenation would be carried out in the Federal Republic of Germany with information and assistance from the United States, and in France.

2.1.3. Subsequently Canada and Italy became Co-Pilots, Norway became associated with the Study, and technical contributions were made by the Central Technical Institute of the Organisation for Applied Scientific Research in the Netherlands. There was also non-official Portuguese interest.

2.1.4. The original NATO document stated that occasional major meetings of all these countries might be held to discuss progress.

2.2. Interpretation

2.2.1. At that early stage in 1972 the United Kingdom commitment was recorded as construction of a full-scale pilot plant at an existing sewage treatment plant at which both domestic sewage and mixed domestic and industrial sewage could be separated for experimental work. The capacity proposed was about 455 cubic metres a day dry weather flow (dwf), equivalent to a flow from about 2,000 people. Supporting laboratory work would be carried out in the nearby sewage works laboratory and at the Water Pollution Research Laboratory at Stevenage (now the Water Research Centre, Stevenage Laboratory).

2.2.2. Whilst the United States was to give design guidance based on their weaker sewage, this was unlikely to enable accurate prediction of performance on the much stronger United Kingdom sewages without some specific comparative tests for translatability.

2.2.3. The proposed plant would include clarifiers, sand filters, carbon adsorption columns, and sludge treatment, together with optional biological oxidation. A flexible choice of unit and of order in a chain of units would be possible and with either steady flow or typically diurnal variation. Control parameters and automated control would be developed to give a final effluent of consistent and pedictable quality.

2.2.4. The plant would be used to evaluate the 'Physical-Chemical Treatment (PCT) Package' (chemically-aided settlement, filtration and carbon adsorption) both in its own right and in comparison with the traditional physical/biological process chain including both activated sludge and biological filter options. The United Kingdom felt this would comply in essence with the spirit of the adopted CCMS AWT Project which was indicated, but not defined in meaningful technical detail, in the CCMS official papers.

2.3. Development

2.3.1. Whilst in the United Kingdom we met these requirements as a first priority in the Study we realised in the early stages that there would be considerable advantage in retaining biological treatment stages even in a predominantly physical/chemical process chain. The low cost, low energy, simple and uniquely effective treatment capability was too valuable to be disregarded in all but the most unusual circumstances.

2.3.2. Other new processes such as for example the Imperial Chemical Industries (ICI) Deep Shaft Process developed initially for protein recovery were being publicised as suitable for adaption to wastewater treatment and some pioneering investigatory work was said to have been done. We kept in touch.

2.3.3. Some current processes for potable water production such as ultrafiltration, reverse osmosis and electrodialysis clearly could have some potential for development to treat wastewater albeit in special circumstances and again we felt that some investigatory work was justified in the context of advanced wastewater treatment.

2.3.4. As there was a demonstrably wide ranging need from the field for better treatment capability and as some basic investigationary work was said to said to have been done on these comparatively sophisticated processes we thought them possibly ripe for development in line with the CCMS second pivotal concept of 'action-orientation'. Therefore we included a watching brief. When results justified it, we proposed to evaluate these processes in our programme.

2.3.5. The Study also went beyond the general CCMS concept of collecting and distilling existing research data: the United Kingdom, Germany and France all built new experimental plants specifically for the Study.

2.3.6. Whilst not originally recorded as a direct commitment, the United Kingdom has contributed much work on direct oxygenation in support of that submitted by France and Germany as committed leaders.

2.3.7. For these and other reasons this unusually extensive study has taken much longer than the two years or so for more normal CCMS projects. Although many options still remain to be evaluated we thought this initial phase should be ended after about six years to review the advanced treatment problem again in depth and in the light of experience we have gained already. Future projects could then be more clearly defined, and hopefully shorter.

2.3.8. As supporting work, the United Kingdom took advantage of the opportunities offered for international co-operation and co-ordination to compare work in the various contributing countries more meaningfully. We proffered draft proposals for harmonising sampling and analyses which were accepted generally though informally. At the same time we discussed the basis for comparative costing and we have subsequently sought typical figures from our co-pilots and associates. We would have liked to establish methodology for evaluating the effect of operation and management on advanced treatment technology but time did not permit.

3. Organisation of the study

3.1. General

3.1.1. By accepting the Pilot Country role the United Kingdom was to be responsible for leading, planning and paying for its own contribution, preparing all necessary reports, and trying to see that action ensued. The United Kingdom also accepted the need to call occasional international meetings to discuss progress.

3.2. International Advanced Wastewater Treatment (Int. AWT) Group

3.2.1. In June 1973 following the CCMS Plenary meeting in Ottawa, the United Kingdom convened a technical discussion on the Project for co-pilots and others interested and initiated the Advanced Wastewater Treatment International Group under their chairmanship.

3.2.2. The Group met subsequently in Burlington (Canada) in February 1974, in Stratford on Avon (United Kingdom) in October 1975, in Paris in November 1975 and June 1976; and in London in June 1978 to review this Final Report. Members are listed in Appendix C.1.

3.3. United Kingdom Committee

3.3.1. The United Kingdom commitment was discharged by the Department of the Environment (DOE) whose then Directorate General of Water Engineering (DGWE) (now Water Engineering Directorate — WED) set up the United Kingdom Advanced Wastewater Treatment Committee (UK AWT Committee) to plan and administer the United Kingdom contribution and Pilot-Country function, the latter in conjunction with the Central Unit for Environmental Pollution (CUEP) of the Department.

3.3.2. The initial committee members were drawn from the several interested divisions within the Department, from the Water Research Centre, from chemical and engineering consultants and from field units of the water industry. Later a representative of the wastewater treatment plant manufacturers and a costing specialist were included. All relevant aspects of the water industry are now involved.

3.3.3. In the early constructional days the main committee set up four steering groups to deal with the individual plant locations at Stevenage, Davyhulme, Coleshill, and the group of four oxygen sites; and three service groups to cover economics, planning and reporting. This is shown in Appendix C.4 Fig. 1.

3.3.4. Later and concurrently with the transfer from the constructional to the operational mode these seven second-tier groups were reconstituted by function as sub-committees to deal with Planning, Monitoring and Economics and a service sub-committee to handle reporting. This is shown in Appendix C.4 Fig. 2.

3.3.5. An organogram of the committee structure together with allocated tasks and lists of members are at Appendices C.4 and C.5.

3.4. Technical workshops and visits

3.4.1. The Federal Republic of Germany held a Workshop in Wuppertal on 10-11 January 1974 attended by the Secretary of CCMS and seventeen representatives from five other nations. It dealt with the direct use of oxygen in the activated-sludge process. Ten papers were given and discussed. Delegates inspected the oxygen activated-sludge pilot plant and main works at Wuppertal-Buchenhofen and the Bayer-AG works at Leverkusen.

3.4.2. Canada held a Workshop in Ottawa and Burlington on 16-17 February 1974, attended by eleven representatives of seven other nations. It dealt with research and development work on Canadian wastewater treatment in general and in particular at the Wastewater Technology Centre, Burlington. Twenty four papers were given and discussed and delegates inspected the Wastewater Technology Centre. Some representatives later visited the Hamilton Works and the Advanced Wastewater Treatment Laboratory at the Ontario Research Foundation.

3.4.3. The United Kingdom held a Workshop in London, Stevenage, Manchester and Coleshill on 29 September — 3 October 1975 attended by the Chairman of CCMS and twenty-six representatives of thirteen other nations. The United Kingdom work on physical-chemical treatment (PCT) and associated processes was reviewed. Delegates inspected the physical-chemical pilot plant at the Stevenage Laboratory of the Water Research Centre, the physical-chemical biological treatment pilot plant at Davyhulme Manchester, and the Advanced Wastewater Treatment pilot plant at Coleshill Birmingham. They also visited the Stevenage Laboratory, the main treatment plant at Manchester and a sludge incinerator at Birmingham. Papers were given on United Kingdom and Canadian work and were discussed.

3.4.4. Delegates also visited the French oxygen activated sludge (OAS) pilot plant operating in Paris in October 1974 and the OAS operational/experimental plant at Dunkerque in February 1977.

3.5. Co-ordination of methods and results

3.5.1. Early in the Study the United States and the United Kingdom considered the linked tasks of co-ordinating methods and comparing results. Clearly results would be of limited benefit if different sampling procedures or varied analytical methods gave rise to misunderstanding or misinterpretation.

3.5.2. Absolute standardisation of sampling and analytical methods if achievable at all would have been a large task involving complex and protracted negotiations inappropriate to the Study. The United Kingdom as Pilot Country prepared and circulated brief notes on sampling methods and analytical procedures for consideration by the technical representatives of the participating countries and these were discussed formally during meetings of the International Advanced Wastewater Treatment Group and informally elsewhere. The few significant differences identified would be referred to when reporting results. For example, the important biochemical oxygen demand (BOD) test was normally carried out over a five-day period, but Norway used a seven-day period, and during the Study the United Kingdom developed a stirred-cylinder laboratory technique for determining settleability of sludge which was thought to be better than the unstirred procedure usually employed.

3.5.3. We circulated a list of recommended units covering such matters as flowrates and capacities for settlement tanks, activated-sludge reactors and biological trickling filters. The units were based generally on the 'Système International d'Unités' (S.I.)

3.5.4. Finally we circulated a questionnaire to elicit information on wastewater characteristics, and on design parameters such as ratings and capacities used in conventional wastewater treatment practice in each participating country. We also enquired about sludge treatment and disposal. We sought estimates of both capital and running costs of civil and mechanical engineering works for notional 'standard' plants serving populations of 10,000, 100,000, and one million.

3.5.5. A more complete return of this information earlier in the Study would have helped us evaluate the work done more conclusively and might have enabled us to draw firmer conclusions. However we are well aware of the many problems and are grateful indeed for all the information we did receive progressively during the long Study.

4. Physical-chemical Treatment

4.1. Review of processes — (a) Introduction

4.1.1. It is not easy to define physical-chemical treatment (PCT) precisely as it overlaps some biological stages. For instance, the settlement forming part of biological activated-sludge treatment is really a physical process, and biological action often occurs during many PCT processes — sometimes to their advantage and sometimes not.

4.1.2. The following were regarded as PCT processes for the Study: chemically-aided settlement, mechanical filtration and carbon adsorption which together form what is loosely termed 'classical PCT'; ammonia stripping, ion exchange, break-point chlorination and reverse osmosis.

4.2. — (b) Process Details

4.2.1. Chemically-aided settlement was used to treat Paris sewage more than two hundred years ago and many hundreds of patents for treatment using chemicals were taken out during the last century in Europe and North America. The development of relatively cheap and effective biological treatment in trickling filters and later in activated-sludge reactors caused a a progressive decline in the use of chemicals and they ceased to be used in conventional wastewater treatment many years ago.

4.2.2. The finely-divided particles of impurities suspended in wastewater carry negative electric charges causing them to repel one another. Coagulation, brought about by the addition of suitable chemicals, neutralises these charges and allows the particles to approach each other more closely. This process takes place more or less instantaneously in a 'flash-mixing' tank.

4.2.3. Flocculation, which encourages the neutralised particles to aggregate together and form 'flocs' large enough to settle well, is accomplished by gently stirring of the coagulated wastewater. Too vigorous stirring may shear the newly formed flocs. Stirring may be needed for about fifteen minutes in a flocculation tank and may be useful even when no chemical coagulant has been used.

4.2.4. The coagulated and flocculated wastewater then passes to sedimentation tanks where the solid particles settle as sludge at an enhanced rate.

4.2.5. Lime, iron and aluminium salts, and polyelectrolytes are commonly used as coagulants. Lime is obtained by heating naturally occurring limestone, chalk and other materials, which releases carbon dioxide to form quicklime. Water is added to quicklime to form slaked lime, calcium hydroxide, $Ca(OH)_2$ — loosely termed 'lime'.

4.2.6. When lime is used to aid coagulation it reacts with the bicarbonate alkalinity present in wastewater to precipitate calcium carbonate and if sufficient be added it raises the pH to a point at which magnesium hydroxide will be precipitated from the magnesium salts also present. Magnesium hydroxide froms a gelatinous floc which promotes rapid and effective settlement, but the proportions of bicarbonate alkalinity and magnesium available influence the process. About 70% of the lime may be recovered by heating the sludges deposited to about 1000°C.

4.2.7. Ferric and ferrous sulphate and chloride are the iron salts used and are waste or by-products of established industrial processes. The aluminium salt usually used is alumium sulphate (alum) made by treating bauxite with sulphuric acid. When using iron salts or alu, the simple reactions with the bicarbonate alkalinity form precipitates of ferric hydroxide and aluminium hydroxide which enhance markedly flocculation and settlement. About 65% of the alum may be recovered by treating its sludges with sulphuric acid to form a solution which can be directly re-used.

4.2.8. Polyelectrolytes are new and relatively costly synthetic substances of high molecular weight with long chain molecules. They act by neutralising the charges of suspended particles or by adsorbing the particles on to their surface. They tend to act selectively and best results are often obtained by using them in conjunction with another coagulant chemical.

4.2.9. Chemically-aided settlement increases both the settlement rate and the proportion of suspended impurities settling-out. Thus it increases the volume of sludge deposited in a settlement tank. Because this sludge contains additional impurities the final disposal may present difficulties not encountered when dealing with sludge derived from traditional settlement.

4.2.10. Mechanical filtration involves passing wastewater, usually after settlement or other treatment, through suitably-graded beds or columns of selected sands and other inert granular media such as anthracite or garnet. Suspended solids are separated out in the media.

4.2.11. Carbon adsorption often follows mechnical filtration in the classical physical-chemical package. A substance that absorbs gases or liquids assimilates them into itself but an adsorptive substance causes them to adhere to its surface, possibly by electrical action. Charcoal is a porous form of carbon and has long been used for adsorbing gases. The number of pores (and therefore the specific surface area) in activated carbon is increased greatly by controlling heating in steam. Activated carbon may be in granules or a powder. Techniques for using granular carbon are similar to those for the mechanical filtration which usually precedes the granular carbon treatment. Powdered carbon is normally used on similar lines to those described for chemically-aided settlement and then mechanical filtration may follow to recover the powder from the effluent before discharge to receiving waters. Adsorption on activated carbon removes dissolved organic impurities not dealt with by biological processes. The carbon process is immune to toxic substances which can affect biological treatment adversely, but it may allow toxic matter to pass forward untreated.

4.2.12. None of the above processes reduce the amount of ammonia significantly. Subject to temperature limitations this is reduced more effectively and easily and cheaply by conventional biological treatment. The following physical-chemical processes do reduce the ammonia content.

4.2.13. Ammonia stripping is carried out in towers similar to the cooling towers associated with electricity generating stations. The process involves raising the pH of the feed wastewater, forming and re-forming wastewater droplets in free fall following pumping the feed to the top of the stripping tower, and finally by promoting intimate air/droplet contact during the fall by circulating large volumes of air through the tower. The ammonia is discharged as a gas.

4.2.14. Selective ion-exchange involves passing wastewater through beds of zeolites (naturally-occurring hydrous silicates) which remove ammonia selectively relative to calcium, magnesium and sodium.

4.2.15. Breakpoint chlorination involves adding chlorine to wastewater to react with the ammonia to form first hypochlorous acid and then chloramines. Adding more chlorine up to the 'breakpoint' converts the chloramines to nitrogen gas.

4.2.16. Reverse osmosis and membrane processes generally involve passing wastewater from other forms of treatment across semi permeable membranes under high pressure. Most commercially-available plants use cellulose acetate membranes. *Reverse osmosis will remove soluble organic* and inorganic matter including bacteria but is very costly and whilst possibly reducing ammonia does not eliminate it.

4.3. Role of the United States — **(a) Background**

4.3.1. In its role as a Co-Pilot the United States reported much experimental and operational work. Pursuing their general advisory role, officials of the Environmental Protection Agency (EPA) helped the United Kingdom set up the Study by commenting on the basic concept of the proposed large-scale Advanced Wastewater Treatment Plant at Coleshill.

4.3.2. In December 1972 six experts from the United Kingdom visited the United States, by kind invitation of the EPA, to confer with their American counterparts on means of achieving the aims of the Study with particular reference to physical-chemical treatment, to exchange information, and to inspect eight experimental and operational plants employing advanced processes. They visited:

a. Blue Plains, Washington DC
Experimental advanced wastewater treatment plants using many physical-chemical, biological and 'pure' oxygen processes.

b. Piscataway, Washington DC
Operation works with activated-sludge followed by physical-chemical treatment, to provide a high quality effluent for discharge to the Potomac River.

c. Salt Lake City, Utah
Pilot plant giving physical-chemical treatment using powdered activated carbon.

d. Colorado Springs, Colorado
Operational works giving physical-chemical treatment to an effluent from an overloaded biological trickling-filter plant to provide a 'second-class' water for power-station cooling and for watering parks and golf courses.

e. Contra Costa, California
Pilot plant with chemically-aided settlement followed by activated-sludge treatment, to provide a 'second-class' water for industry.

f. Pomona, Los Angeles, California
Experimental advanced wastewater treatment plants using many physical-chemical and biological processes.

g. South Lake Tahoe, California
Operational works with activated-sludge followed by physical-chemical treatment. The effluent is pumped to a new artificial recreational lake.

h. Freehold, New Jersey
   Operational 'packaged' works contained in the shell of a house and giving physical-chemical treatment.

4.4. — (b) Influence

4.4.1. General advice from the United States of America and particularly from that visit had a significant influence on the United Kingdom contribution to the Study, particularly on the Coleshill plant then being designed. The following proposals were agreed with or confirmed by the American experts:

a. As wastewater characteristics and weather conditions are both subject to uncontrollable and significant variations, process comparison would be more valid and made more quickly by operating parallel treatment streams.
b. Treatment units designed to deal with an average daily flow of 450m^3 (100,000 gallons) might be reasonably free from the scale effects that prevent results obtained on small pilot-plants from being adopted with confidence for operational works.
c. Whilst facilities should be provided for simulating the daily variations in flow-rate at operational works to make plant conditions as realistic as possible, some advanced processes might work better at more constant rates of flow. Therefore balancing facilities were desirable, and these could also be used in developing and optimising conventional processes.
d. Such a pilot-plant should not be used for researching into new equipment and processes but for developing, proving and demonstrating them for use in operational practice.
e. To make effective use of the high capital investment in the large experimental plant we would need to provide adequate continuous staffing and sufficient specialists such as instrument technicians.
f. As physical-chemical and biological processes were to some extent complementary we would need to evaluate many process combinations.
g. Removal of ammonia and nitrogen might be the most difficult stages of treatment, particularly by physical-chemical means.
h. Whilst much work was already going on in the United States we would always need to evaluate and prove processes under the different conditions and different requirements applying in Europe.

4.4.2. These concepts were incorporated in our plans for Coleshill and into the associated work for the Study. The Research Laboratory at Stevenage had already established a small pilot-plant in a 'path-finding' role and we set up an additional pilot-plant at the Davyhulme Wastewater Treatment works near Manchester to help evaluate the many options open. The Stevenage plant was already provided with a stripping tower to evaluate that process for ammonia removal, but following the visit to the United States it was also equipped with a sidestream for biological nitrification-denitrification. We have already referred to the joint initiative of the United States/United Kingdom in co-ordinating methods and comparing results. Advice and views from the United States were always freely available throughout the Study and this helped us considerably in programming and subsequent operations.

4.5. Summarised Process Characteristics

4.5.1. From the widely varying advice we received, much in detail, we selected the following as significant advantages of physical-chemical processes:

a. Not affected by 'toxic' wastes and relatively unaffected by shock loads and low temperatures

b. Will remove non bio-degradable and some bio-degradable substances that penetrate traditional treatment

c. Can be designed to remove specific pollutants and provide a range of predictable effluent quality to match discharge constraints

d. Can be brought into operation quickly and controllably, and treatment provided to match the load imposed

e. Amenable to application of high technology, automated operation and control, and chemical engineering experience

f. Requires less land than conventional treatment and using modern techniques can be made nuisance free either within or under urban development

g. Can be made aesthetically attractive and provide the good working conditions needed for the high level managers and operatives required

h. Produces readily dewaterable sludge (with lime) which is easily disposable.

4.5.2. The following were adjudged the main disadvantages:

a. Not the most cost effective way of treating normal domestic wastewater to comply with the normal discharge requirements current in the United Kingdom

b. Is energy intensive and action may be selective in comparison with traditional plants

c. Does not remove all substances which can be removed by traditional treatment such as urea and cyanide. It can generate its own hazards, for example, hydrogen sulphide in activated carbon adsorption towers

d. The sophisticated equipment used requires highly skilled and hence costly operation and management and support services

e. Treatment is dependent on external supplies such as chemicals and thus is sensitive to commercial and industrial action remote from the site

f. Industrial type plant may discourage its siting above ground within developed areas of high amenity value

g. Large volume of chemical sludge from using alum and iron salts as coagulants may be difficult to dewater and dispose of.

4.5.3. It is not feasible to say dogmatically when physical-chemical treatment should be used in preference to traditional treatment but its application could be considered when:

a. The wastewater is mainly industrial and the pollutants to be removed are mainly chemical

b. Effluents have to be of very high quality such as a prelude to re-use and where varying standards may be applied such as seasonally

c. Traditional plants are continually overloaded or have transient peaks in load

d. Less stringent discharge conditions may apply such as for discharge to estuaries and the sea

e. Site is restricted such as at a coastal resort discharging to the sea.

4.6. Work in the United Kingdom — (a) Introduction

4.6.1. Work was carried out on laboratory scale and small single-stream pilot-plant scale at the Stevenage Laboratory, on a single-stream pilot-plant at Davyhulme Wastewater Treatment Works in Manchester, on a large two-stream pilot-plant at the Coleshill Advanced Wastewater Treatment Plant near Birmingham and on an operational scale plant at Cliff Quay Wastewater Treatment Works, Ipswich. Appendices B5/1 to B5/6 give information on the plants.

4.6.2. The following table indicates the general type of wastewater treated but wastewater characteristics at any given works may vary widely. Two sources are available at Coleshill, one domestic and one containing industrial effluent. The domestic wastewater was used throughout the Coleshill work reported.

Parameter (mg/l except for pH)	Stevenage	Davyhulme	Coleshill	Ipswich
pH	—	7.5	7	7.7
Suspended solids	490	306	222	486
BOD_5	450	253	236	338
COD	950	653	562	735
TOC	—	141	121	—
Ammoniacal nitrogen	35-45	29	35	33
Organic nitrogen	—	—	17	—
Ortho-phosphate (as P)	12	4	7	—
Total phosphorus (as P)	21	6	11	9
Anionic detergents	—	8	17	9
Alkalinity (as Ca CO_3)	450	206	246	—
Calcium	102	73	42	—
Magnesium	3.7	10	13	—

The Stevenage wastewater is also domestic in origin and 'strong' by United Kingdom standards. The Coleshill wastewater derived from modern housing development is 'weak'. Wastewater at Davyhulme contains various industrial effluents and the composition is liable to change without warning. Ipswich wastewater contains brewery wastes and effluents from food and heavy engineering manufacture.

4.7. — (b) Stevenage: evaluation of coagulants

4.7.1. Jar tests in the laboratory with 20-litre samples to provide sufficient sludge for examination used doses of 50-400 mg/l ferric chloride, 50-400 mg/l aluminium sulphate (alum) and 50-600 mg/l lime. After adding chemical, the wastewater was stirred quickly for one minute and slowly for fifteen minutes to simulate the flash-mixing and flocculating stages referred to previously. Supernatant liquor was decanted after settling for one hour. The quiescent settlement gave better results than the continuous-flow settlement on operational works which often have a nominal average retention of four hours or more. Appendix A1 gives results.

4.7.2. Suspended solids were removed well at about 75% in the control test without chemicals. Around 90-95% were removed with doses of 50 mg/l ferric chloride, 200 mg/l alum, and 100 mg/l lime. Removals were best using doses of 200 mg/l ferric chloride (99%), 400 mg/l alum (98%) and 600 mg/l lime (96%).

4.7.3. Removal of biochemical oxygen demand (BOD) varied widely in the control tests ranging from 28% to 56% of BOD$_5$, the latter being higher than expected normally. A dose of 50 mg/l ferric chloride removed 52%, of 200 mg/l alum removed 60%, and of 100 mg/l lime removed 80% of the suspended solids. Removals were best with doses of 200 mg/l ferric chloride (65%), 400 mg/l alum (67%) and 300 mg/l lime (84%).

4.7.4. The chemical demand (COD) of a wastewater indicates the oxygen needed theoretically to oxidise the carbonaceous matter completely to carbon dioxide and water. The removal of COD in control tests ranged between 43-54%, and reached a maximum of 72% using a dose of 200 mg/l ferric chloride, 76% using a dose of 400 mg/l alum, and 77% using a dose of 300 mg/l of lime.

4.7.5. Appendix A1 gives detailed costs of chemicals but at the doses giving best removals of suspended solids they were:

Coagulant	Dose (mg/l)	p/m³ wastewater treated in 1977
Ferric chloride	200	2.8
Alum	400	1.9
Lime	600	0.46

The cost of chemicals is not the only one to consider: dosing automatically may have a significant effect.

4.7.6. Chemicals added to wastewater to aid settlement usually form more sludge, incrementally with both the additional suspended or colloidal impurities settled-out and with the chemicals added. This is important as the cost of treatment and disposal of sludge on even a conventional treatment plant may represent half the total capital and running costs.

4.7.7. The doses of chemical removing most suspended solids (4.7.2. above) increased the volume of sludge by 167% with ferric chloride, 250% with alum and 225% with lime. Both ferric chloride and alum gave sludges with low dry solids content implying more difficult de-watering but doses of lime up to 300 mg/l gave a sludge with a higher dry solids content implying easier de-watering.

4.7.8. The following summary table shows that lime offered many advantages; the doses quoted are those thought most effective for each chemical:

Parameter		Control figures	50 mg/l ferric chloride	200 mg/l alum	100 mg/l lime
SS removed	%	76/72/76 *	95	97	92
BOD$_5$ removed	%	28/37/65	52	60	80
COD removed	%	43/54/44	67	59	73
Chemical cost p/m^3		–	0.7	1.0	0.08
Sludge: volume mg/l		9/12/8	16	31	13
Sludge: dry solids content	%	3.5/3.7/3.9	3.6	2.0	7.5

*76 is the control figure for 50 mg/l ferric chloride
72 is the control figure for 200 mg/l alum
76 is the control figure for 100 mg/l lime
and so on.

4.7.9. We did experiments using mixed coagulant chemicals. In one series a basic dose of 500 mg/l of lime was used as the best performance with lime appeared to be with doses between 300 and 600 mg/l (Appendix A1). Ferric chloride with doses between 2.5 mg/l and 15 mg/l (as Fe) and a selection of polyelectrolytes dosed at 0.1 mg/l were used as supplementary chemicals. Some additions helped but some removed less. These chemicals gave little benefit but later work using ferric sulphate showed more promise.

4.8. — (c) Coleshill: evaluation of coagulants

4.8.1. Ferric sulphate was used first (instead of ferric chloride on grounds of cost and availability); then alum, and lime. The rate of flow of wastewater was steady. The retention of 12 minutes and 40 minutes respectively in the flash-mixing and flocculating stages were high being designed to cope with the high flow rates resulting from diurnal flow variation. Retention in the settling-tank for chemically-dosed feeds was 1.1 hours giving an upward-flow velocity of 2.7 metres an hour but such conditions would not be satisfactory for unaided settlement and so 2.2 hours retention was allowed for the control stream (to which chemicals were not added) giving an upward-flow velocity of 1.4 metres an hour. Appendix A2 shows results.

4.8.2. Less suspended solids and BOD_5 were removed in the control stream than in the one-hour jar tests at Stevenage: 33% against 72%-76% and 15% against 43%-54% respectively. The quiescent settlement in the laboratory was more efficient than that in the field on the weak Coleshill wastewater. Removal with alum was poor — much less at equivalent doses that that at Stevenage. Only 69% suspended solids were removed with a dose of 50 mg/l, and performance deteriorated markedly at doses of 60 mg/l and 70 mg/l. Ferric sulphate and lime worked well and comparably in some respects. Doses of 76 mg/l ferric sulphate and 300 mg/l lime removed 92% and 91% of suspended solids and 74% and 70% of BOD_5 respectively. But the pH of the limed effluent at 10.9 was high for direct discharge to receiving waters or for further treatment on biological trickling filters.

4.8.3. Removal of phosphorus was also examined and is detailed later. Alum did not do this satisfactorily as a dose of 70 mg/l only removed 67%, but doses of 50 mg/l ferric sulphate and 250 mg/l lime removed 92%.

4.8.4. Slightly more sludge ensued from both alum and ferric treatment than from unaided settlement. However, neither sludge from alum not ferric sulphate thickened easily, and both showed signs of being difficult to dewater on a standard filter press. Conversely, whilst the volume of sludge from lime treatment was much higher it thickened and filtered well. As the sludge aspect is important and lime is cheap we concentrated on settlement with lime, and investigated the possible advantages of using ferric sulphate as a supplementary coagulant.

4.8.5. High removal of solids using lime as a coagulant leaves an effluent with a high pH. High removal of solids may be unnecessary and high pH undesirable in some circumstances such as discharge to an estuary. The pH of limed effluent should be kept below 11 when fed to a following plug-flow biological activated-sludge stage. A dose of 250 mg/l of lime was selected at Coleshill to give a good balance of advantage for a partially-treated effluent. This removed 78% of suspended solids, 42% of BOD_5 and 92% of ortho-phosphate. Actual values were 46 mg/l, 88 mg/l and 0.4 mg/l respectively indicating an effluent suitable for most estuarine discharges.

4.8.6. If lime treatment is to form part of a full physical-chemical treatment array we would need to remove more solids using a high dose of lime to settle the gelatinous flocs of magnesium hydroxide which aid clarification. The figures in Appendix A2 indicate that magnesium was preceipitated at a lime dose of 300 mg/l but an experimental dose of 400 mg/l was selected to allow for variations in the wastewater characteristics. Some 90% of suspended solids, 69% of BOD_5 and 99% of phosphates were removed at that dosage.

4.8.7. During the series of experiments with supplementary chemicals, doses of 5 mg/l, 10 mg/l and 15 mg/l of ferric sulphate (as Fe) were used in combination with the basic lime doses of 250 mg/l and 400 mg/l. A dose of 10 mg/l ferric sulphate added to 250 mg/l lime increased the removal of suspended solids from 78% to 93% and the removal of BOD_5 from 42% to 56%, without increasing the volume of sludge much or reducing the dry solids content of the sludge significantly. The same supplementary dose added to 400 mg/l lime only increased the removal of suspended solids and BOD_5 marginally — from 89% to 93%, and from 68% to 71% respectively — but reduced the dry solids content of the sludge considerably. Supplementary aid was more effective generally at the lower basic dose of lime.

4.8.8. Appendix A3 shows the cost of chemicals per m^3 of wastewater treated at Coleshill against removal of suspended solids as the most significant parameter. This graph illustrates the advantages of lime in general and also the benefit gained by adding ferric sulphate to a basic dose of lime of 250 mg/l.

4.8.9. Appendix A4 shows the notional costs of treating 45,000 m^3/d of wastewater by chemically-aided primary settlement and conventional biological treatment including de-watering sludge by filter press.

4.8.10. Experiments using retention times of 0.5, 1 and 2 hours at various lime doses to evaluate the effect of tank size gave the following results;

Retention (h)	Lime dose (mg/l)	% removals		
		SS	BOD_5	COD
0.5	250	0	6	27
0.5	400	44	50	58
1	200	75	27	68
1	250	78	42	65
1	400	89	53	68
2	200	78	39	58
2	250	88	41	63

These figures confirmed that about 1 hour retention was sufficient and less than 0.5 hour was not adequate.

4.8.11. Most operational works experience diurnal variations in flow, and as the Coleshill plant is equipped to simulate any flow pattern the effects of varying and steady rates of flow on lime-aided settlement were compared. Total daily flow was the same to each experimental stream, but one stream was fed at a steady rate throughout each day and the other at rates corresponding to those at the large operational works adjacent (maximum rate about 1.7 times average, minimum about 0.3 times). Each stream was limed to a constant pH, times of retention for flash-mixing, flocculation and settling-tank were comparable and as noted above.

4.8.12. During the first experiment the wastewater entering the settlement tank was limed to a pH of 9.5. Results were:

Parameter	Liming to pH 9.5 mg/l			
Raw wastewater				
pH	7.3			
SS	286			
BOD_5	195			
COD	723			
Settled effluent (pH 9.3/9.4)	Steady flow		Diurnally-varied flow	
	mg/l	% removal	mg/l	% removal
SS	71	75	62	78
BOD_5	173	11	175	10
COD	332	54	369	49

Both steady and varied rates of flow gave poor removal.

4.8.13. During a second experiment the feed was limed to pH 11.2 and results were:

Parameter	Liming to pH 11.2			
Raw wastewater				
pH	7.3			
SS	335			
BOD_5	320			
COD	711			
Settled effluent (pH 11.2)	Steady flow		Diurnally-varied flow	
	mg/l	% removal	mg/l	% removal
SS	40	88	67	80
BOD_5	164	49	176	45
COD	248	65	241	56

The removal with steady flow was the better.

4.8.14. Recirculating sludge from the settling tank to the feed had improved performance on the Stevenage pilot-plant and was tried at Coleshill but without success. Effluent qualities deteriorated at lime doses of both 250 mg/l and 400 mg/l and at all recirculation rates from 1:1 to 2.75:1, probably because of the increased solids loading on the settling tank. The following figures extracted from the table in paragraph 4.6.2 above are significant in this regard:

Parameter (mg/l)	Stevenage wastewater	Coleshill wastewater
Alkalinity (as $CaCO_3$)	450	246
Magnesium	3.7	13

4.8.15. The lower alkalinity of the Coleshill wastewater required a relatively low dose of lime to achieve a given increase in pH. Thus relatively low doses of lime will attain the pH at which the benefit of precipitating gelatinous magnesium hydroxide begins and Coleshill wastewater contains much more magnesium than that at Stevenage. Recirculating sludge and thus increasing interparticle contact and floc-formation can be useful where magnesium is limited as at Stevenage but its disadvantages prevented any general benefit at Coleshill.

4.9. — (d) Stevenage, Davyhulme and Coleshill: lime-aided settlement

4.9.1. The feeds to settling tanks were limed to pH 10, 10.5, 11.0 and 11.5 successively at each of the three plants operating at steady flow rates. Whilst detailed results are shown in Appendix A5 the following abstracted figures are of particular interest:

		Stevenage	Davyhulme	Coleshill
Tank retention	h	1.1	1.1	1.1
Tank upward flow velocity	m/h	1.1	1.6	2.7
Average magnesium content of wastewater (para 4.6.2)	mg/l	3.7	10	13
Control, no liming				
SS of feed	mg/l	–	472	185
% removal		–	58	12
Liming to pH 10				
SS of feed	mg/l	430	518	254
% removal		39	80	46
Liming to pH 10.5				
SS of feed	mg/l	309	327	196
% removal		36	85	65
Liming to pH 11				
SS of feed	mg/l	198	315	216
% removal		70	80	85
Liming to pH 11.5				
SS of feed	mg/l	212	321	219
% removal		87	79	86

4.9.2. Several factors have influenced the results. At Davyhulme the low upward-flow velocity in the settling tank and the high suspended solids content in the feed both tended to give good removal, and masked the benefit of magnesium precipitation known to be substantial around pH 11. However the effect of the magnesium is clear at Stevenage although 70% removal at pH 11 was not a good figure. This was due partly to the basic shortage of magnesium, and partly because the feed during the work was remarkably weak but 87% removal was attained at pH 11.5. At Coleshill, removal without liming was poor, again reflecting the high upward-flow velocity and the relative difficulty of settling-out a weak wastewater. However the magnesium content was high and the effects of its precipitation at pH 11 are well demonstrated.

4.9.3. The relative amounts of sludge are interesting:

		Stevenage	Davyhulme	Coleshill
Average alkalinity of feed (as Ca CO_3)	mg/l	450	250	246
Liming to pH 10				
SS removed	mg/l	166	412	–
Sludge produced	kg/m^3	1.07	0.48	–
Liming to pH 10.5				
SS removed	mg/l	110	273	128
Sludge produced	kg/m^3	0.94	0.62	0.48
Liming to pH 11				
SS removed	mg/1	139	253	184
Sludge produced	kg/m^3	1.03	0.54	0.62
Liming to pH 11.5				
SS removed	mg/l	185	255	189
Sludge produced	kg/m^3	1.13	0.62	0.74

More lime was needed to raise the pH at Stevenage than at Davyhulme or Coleshill. As virtually all lime settled out in the sludge, the sludge production at Stevenage was consequently high.

4.9.4. Removal of biochemical oxygen demand was erratic at Davyhulme for example being substantially less at pH 11 than at pH 10.5. This presumably reflected varying proportions of soluble biochemical oxygen demand (which is not removed by settlement) occurring from changed discharge of industrial effluents.

4.9.5. Appendix A6, covering reasonably typical weeks during the work, shows the variability of Davyhulme wastewater and the beneficial smoothing or 'peak-lopping' effects of chemically-aided settlement.

4.9.6. Appendix A7 shows the improved removal of heavy metals at Davyhulme with lime-aided settlement.

4.9.7. Two unexpected developments were noted at Davyhulme during liming. There was no separation of grease, and the soluble biochemical and chemical oxygen demands of the limed effluent were actually higher than the corresponding figures for raw wastewater. These observations indicated that adding lime results in complex chemical reactions, to be borne in mind when assessing the net advantage of the process.

4.10 — (e) Cliff Quay: evaluation of polyelectrolyte coagulants

4.10.1. This work by the Anglian Water Authority on field scale using operational settling tanks forms the first part of a project intended to evaluate alum, ferric sulphate, lime and polyelectrolytes as aids to settlement.

4.10.2. Cliff Quay works has a dry-weather flow of about 25,000 m^3/d and gives primary settlement only before discharging to the adjacent tidal reach of the River Orwell. Liquid sludge is dumped at sea. Unaided primary settlement produces an effluent with around 150-250 mg/l suspended solids and 200-275 mg/l BOD_5 from a wastewater containing considerable quantities of industrial effluent. The former River Authority proposed an effluent standard of 70 mg/l suspended solids and 140 mg/l BOD_5. Extensive and broadly successful experiments at the works some years ago (funded partly by the Department of the Environment) aimed at attaining standard by secondary treatment on biological 'roughing' filters with plastic media. The Anglian Water Authority being aware of the work under the CCMS AWT study decided to evaluate chemically-aided settlement as an alternative means of reaching the proposed standard and the Department agreed to meet part of the cost.

4.10.3. Following preliminary laboratory work the Authority arranged to divert one-third of the flow reaching the works, dose it with chemicals, and settle it in one of the six identical circular settling tanks on the works. The other two-thirds of the flow acting as control, were settled in two tanks (three tanks being kept empty). Chemical and control sludges were kept separate. Ideally the control sludge liquors should have been returned to the control stream and chemical liquors to the chemical stream but this was not possible without expensive alteration. During most of the experiments the control sludge liquors were returned to the inlet of the whole works and chemical sludge liquors were discharged untreated. The flash-mixing and flocculation stages on the chemical stream were provided respectively by the turbulent conditions below the flow-measuring flume and by a long approach channel to the settling tank giving about 5 minutes retention.

4.10.4. The settling tanks in both streams provided 4.5 hours retention with an upward flow velocity of 3.3 m/hour. Appendix A8 gives results.

4.10.5. During dosing at 3 mg/l of Zetag 92 some rising sludge was observed in the tank and desludging was difficult owing to the high solids content of the sludge.

4.10.6. Before dosing at 4 mg/l of Zetag 92 the tank was emptied and cleaned. At that dose rate large flocs formed in the long approach channel and rising sludge became a serious problem. Within two days the tank desludging pipes blocked. The tank was again emptied and cleaned and during the rest of this experiment which was reduced to five days to save chemical costs the rising sludge and desludging difficulties continued.

4.10.7. At the dose of 4 mg/l of Zetag 92 the effluent from this chemically-aided settlement of a weak wastewater due to prolonged heavy rain during the period concerned had a suspended solids content of 67 mg/l and a BOD_5 of 117 mg/l but the operating difficulties precluded continuing using this high dose.

4.10.8. The proposed standard of 70 mg/l suspended solids was not achieved at lower doses. The 3 mg/l dose gave an effluent with 92 mg/l suspended solids and 124 mg/l BOD_5, compared with the proposed standard of 140 mg/l.

4.10.9. In general terms, increased doses of chemicals reduced suspended solids, BOD_5 and COD. Treated effluents, even at very low doses, were always better than control effluents and more consistent. The most cost-effective dose of Zetag 92, in terms of chemical cost only, was 0.25 mg/l (the chemical cost only at that dose being 0.04p/m^3 wastewater treated). Removal of phosphate was not improved materially.

4.10.10. Operational difficulties precluded accurate measurement of sludge production but the total solids figures for sludges from chemically-aided settlement were not discouraging.

4.10.11. Work has now commenced on the alum phase of the experiments.

4.10.12. The Anglian Water Authority have recently embarked on other operational-scale work aimed at using chemically-aided settlement to relieve overloaded works and/or to raise the quality of works effluent.

4.11. Work in Norway

4.11.1. Norwegian receiving waters usually provide large dilution for the loads to be dealt with from the many small communities, thus most Norwegian wastewater treatment works give only primary treatment. However standards — including effluent standards — are rising, but two considerations militate against what might seem to be the obvious next step of adopting biological secondary treatment. First, the cold Norwegian winters affect biological processes adversely and second, plant-nutrients in the works effluents — which biological secondary treatment does not remove — promote eutrophication in receiving waters. Phosphate and nitrate are principally concerned, but as the former is thought to trigger eutrophication and as much of the nitrate drains from fertilised farmland direct to rivers and lakes and thus cannot be controlled, removal of phosphate has become an important aim in Norwegian wastewater treatment.

4.11.2. Two-stage tank treatment is often uses in practice and frequently only the second stage is chemically-aided. This configuration is adopted partly to increase removals and partly to reduce the consumption of chemicals.

4.11.3. Experiments showed that using lime to reduce phosphorous in the effluent to under 0.5 mg/l (as P) was largely dependent on pH and that the chemical doses depended on wastewater alkalinity. Favourable ranges were pH 5-6 for alum and iron salts, pH 11.2 and above for lime, and pH 8 and above for doses of iron and lime combined. COD removals using alum, iron and lime were then about 70%, 60% and 55% respectively.

4.11.4. In associated studies the sludge produced with alum and iron precipitants was found generally to confirm the hypothesis that most suspended solids were flocculated and settled out, that phosphates were precipitated as $AlPO_4$ (or $Fe\ PO_4$) and that surplus chemicals were precipitated as hydroxides. No such hypothesis was established with lime treatment which commonly produced 2-2.5 times as much sludge as unaided settlement.

4.11.5. The advantage of precipitating the gelatinous flocs of magnesium hydroxide in lime-aided settlement was referred to in para 4.2.6, the degree depending among other things on wastewater magnesium concentration. An operational lime-aided primary settlement works near Oslo has had 5% seawater added to its feed since 1974 giving a marked reduction in lime consumption and more efficient settlement. Laboratory work indicated that this practice increased concentration of magnesium and precipitated the hydroxide at lower pH. Adding 2%-3% of seawater to the wastewater which was low in magnesium in addition to 200 mg/l-300mg/l of lime seems to be as good as or better than a dose of 500 mg/l of lime in conventional lime precipitation.

4.11.6. The marginally increased salinity of the effluent was not important in a primary treatment plant discharging to tidal waters. Sludge production was about the same as from conventional lime precipitation.

4.11.7. This ingenious development may well find numerous applications in coastal and estuarine situations, and investigations continue.

4.12. Work in France

4.12.1. A project near Nice was directed at solving the problems facing the authorities of the French Mediterranean area in treating their sewage. These included locating the plant, protecting the receiving water, choice of plant to cope with large increases in polluting load, and construction of plant with relatively low running costs.

4.12.2. Between March and July 1976 tests were carried out near the Nice-Ferber pretreatment plant on the treatment of domestic sewage from tourist areas. The tests concentrated on physical-chemical methods of treatment and included compact separation techniques using decantation or flotation processes because of their application to both coastal and mountainous tourist areas.

4.12.3. The main objectives of the study were:-

a. Elimination of colloidal or suspended substances in the domestic sewage
b. Definition of the conditions for the withdrawal and disposal of the sludge
c. Research into the ability of physical-chemical purification to eliminate pathogens and an examination of independent disinfection processes especially by means of ozone

4.12.4. The first part of the study comprised:

a. Determining the effects on the characteristics of the effluent of the use of combinations of two or three of the following reagents:-
ferrous sulphate, ferric chloride, aluminium sulphate, lime and polymers
b. Adaptability to changes in type and level of pollution and determination of the permissible real and surface hydraulic loads for separation by decantation or flotation
c. Researching into the relationship between quantities of reagents and flow of sewage
d. Ascertaining the reliability and manageability of the equipment
e. Studying the economic aspects of physical-chemical purification according to the separator and reagents used
f. Examining individual environmental problems
g. Studying the construction parameters of physical-chemical treatment.

4.12.5. At the same time it was considered necessary to reduce the sludge to as small an amount as possible and tests were carried out to:

a. Establish the properties of the sludges derived from different chemical conditioning
b. Determine the effects of the various types of mechanical dewatering equipment
c. Assess the costs of the various types of treatment.

4.12.6. The study of the disinfection of waste water included:

a. Determining the results of physical-chemical treatment on the absorption of microbes by metallic hydroxides
b. Determining the results of increasing the pH to 11.5 and above
c. Evaluating the use of ozone and ultr-violet rays after physical-chemical treatment.

4.12.7. The experimental site was situated near Nice airport and a pump with a capacity of 70 m³/h delivered sewage from the pre-treatment station at Nice-Ferber. The site was laid out so that the operation of a number of pilot-plants could be compared at the same time. Eight different types of flotation or decantation equipment were tested using combinations of two or three coagulants with seven different sewage strengths. Typical results are summarised in the following table: —

Concentration

AVERAGE RESULTS OBTAINED FROM THE USE OF
DIFFERENT COAGULANTS

Chemical conditioning	Dosage g/m³	Flow in metres/h	Removal (%)			Sludge		
			Total suspended Solids	COD	BOD_5	Concentration g/1	Volume 1/m³	Suspended solids g/m³
			Decantation					
Aluminium sulphate	200	18	75	68	70	8-9	20	160-180
+ polyelectrolytes	1							
Ferric-chloride	116	15.3	78	65	70	3-10	20-25	160-200
+ polyelectrolytes	1.5							
Ferrous sulphate	200	16	76	70	67	10-12	25	250-300
+ Lime	140							
+ polyelectrolytes	1							
Aluminium sulphate	160	18.7	77	70	68	10-11	15	150-160
+ Lime	40							
+ polyelectrolyte	1							
Ferric chloride +	120	20	80	71	70	12	15	180
Lime	60							
+ polyelectrolyte	0.5							
Lime	420	17	60	65	48	12-18	25-30	370-420
+ polyelectrolyte	0.5							
			Flotation					
Aluminium sulphate	160		65-78	58-70	65-75	55-70	2.5-3	160-180
+ polyelectrolyte	0.8	7-12						
Ferric chloride	110		65	70	75	45-60	2.5-3	160-180
+ polyelectrolyte	1.5							
Ferrous sulphate +	160	7	50	60	60	45-60	5-8	280-300
Lime	180							
+ polyelectrolyte	1.5							
Aluminium sulphate +	175		68	71	66	55-60	2.5-3	160
Lime	70							
+ polyelectrolyte	1.4							
Ferric chloride +	120	7-10	60-85	60-75	60-70	40-70	3-4	170-200
Lime	80							
+ polyelectrolyte	1.3							
Lime	420	8	50	63	55	50-80	5-8	370-420
+ polyelectrolyte	1.2							

4.12.8. It was evident that:

a. Chemical conditioning of dilute sewage gave more favourable results than those for normal and strong sewage

b. Polyelectrolytes were used with single reactants and their doses were then important. When used in conjunction with two other coagulants the polyelectrolytes were not essential.

c. The removals with ferrous sulphate and lime were similar to those obtained with other combinations in spite of the use of lower doses of iron and higher doses of lime than normal

d. The need for coagulant aid to settle strong sewage was evident but the optimum dose was not always proportional to the concentration of pollutant. Only 20%-25% more reagent has needed to deal with a 100% increase in suspended solids load. This demonstrated the need for an accurate investigation of the drainage system and the sewage to be treated before designing a project. The effects of separation of sewage and tests with various reactants should be essential parts of an economic study to determine the costs of treatment

4.12.9. The second part of the study was directed at the sludges from the use of various combinations of coagulants and these are summarised in the following table: —

Chemical conditioning	Dosage g/m³	Sludge produced in grams dry solids per m³ of treated sewage	Properties of the sludge produced			
			Volume in litres per m³ of sewage		Solids in grams per litre	
			Decantation	Flotation	Decantation	Flotation
Aluminium sulphate and poly-electrolyte	140-160 0.75-1	160-180	16-18	2.6-3	9-11	55-65
Ferric chloride and poly-electrolyte	120 1	160	16	2.9	9-11	50-60
Aluminium sulphate and lime and poly-electrolyte	160 40 1	200	16.6	3.3-3.6	11-13	55-60
Ferric chloride and lime and poly-electrolyte	100 50 1	180-200	12.85-14.3	3.1-3.8	12-15	50-60
Ferrous sulphate and lime and poly-electrolyte	150-250 150-250 1	270-350	19.5-25	5-8	12-16	45-60
Lime and poly-electrolyte	400-500 1	350-400	19-25	5-8	16-20	50-80

4.12.10. The properties and analyses of the sludges obtained by different means were determined and recorded. The sludges were tested for their suitability for vacuum filters, pressure filters or centrifuges and the advantages and disadvantages listed for each.

4.12.11. The third part of the work was directed at the elimination of microbial pollution and was based on determination of E Coli and faecal streptococci in the effluents after treatment by the following combinations:

a. Ferric chloride and polyelectrolyte
b. Aluminium sulphate and polyelectrolyte
c. Aluminium sulphate, lime and polyelectrolyte
d. Ferric chloride, lime and polyelectrolyte
e. Ferrous sulphate, lime and polyelectrolyte.

This was followed by studies of the effects of chemical conditioning on the elimination of viruses and salmonellae, of disinfection by ozone and by ultra-violet rays.

4.12.13. It was concluded that physical-chemical treatment using ferric chloride, aluminium sulphate or ferrous sulphate, possibly supplemented with lime reduced the faecal germ counts considerably. The reduction of faecal streptococci and Escherichia coli subject to binary or ternary treatment was about 10^2 and greater reductions had been achieved with ferrous sulphate, lime and polyelectrolyte in combination. Chemical treatment had also reduced viruses and salmonella by about 10 to 10^3. Increasing the pH level to 11.5 by adding lime had inactivated viruses and salmonellae completely and eliminated faecal contamination.

4.12.14. Disinfecting the effluent from physical-chemical treatment by ozone with a residual of 0.5 ppm had destroyed viruses and salmonella at a cost of 6 to 7 centimes per cubic metre of effluent.

4.12.15. Tests with ultra-violet rays had neither reduced the germ count and viruses effectively nor eliminated salmonellae.

4.12.16. The above information is based on a report published in 1976 by Agence de Bassin Rhone Mediterranee Corse entitled "Epuration Physico-Chemique de Moindre Encombrement eaux usees domestiques, Synthese des Essais de Nice Ferber".

4.13. Phosphorous removal — (a) Introduction

4.13.1. Removing the plant-nutrient phosphorus, which cannot be done significantly by conventional wastewater treatment, has already been mentioned in connection with reducing eutrophication in rivers, lakes and other bodies of water. It formed an important part of the successful campaign to clean up the Great Lakes in the United States and Canada.

4.13.2. Phosphorus from human wastes is always present in domestic wastewater. It is also contained in synthetic detergents and certain industrial and agricultural effluents. The following table shows amounts of the various types in one wastewater in the United Kingdom:

Type		mg/l (as P)	
Ortho-phosphate	soluble	6.6	
	insoluble	5.8	
	total		12.4
Polyphosphate	soluble	1.1	
	insoluble	4.5	
	total		5.6
Organic phosphorus	soluble	0.4	
	insoluble	2.8	
	total		3.2
TOTAL PHOSPHORUS	soluble	8.1	
	insoluble	13.1	
	total		21.2

4.13.3 An extensive Canadian survey showed lower figures than those in the United Kingdom. Total phosphorus in raw wastewater varied between 2 and 18 mg/l with an average of 8 mg/l, and final effluents from biological activated-sludge works contained between 1 and 8 mg/l with an average of 5 mg/l.

4.13.4. The multivalent ions of the aluminium and iron salts used in chemically-aided settlement combine with the soluble phosphates in wastewater to form insoluble precipitates, and the organic phosphorus and polyphosphates present are also removed by a complex combination of precipitative and adsorptive reactions (polyphosphates also tend to be *hydrolyzed in sewers and during passage through conventional treatment* works). The mechanisms forming insoluble phosphates are somewhat different when lime is used and are dependent on the pH value.

4.13.5. Some phosphorus is essential for the proper functioning of all biological treatment processes but only a small amount and perhaps as little as only 1% of the BOD_5 content of the feed liquor.

4.13.6. The work reported below formed part of an extensive Canadian programme of laboratory testing and associated operational works trials devised in connection with the Great Lakes Agreement under which, in Ontario alone, 170 existing works serving 5 million people were required to produce effluents containing not more than 1 mg/l total phosphorus.

4.14. (b) Laboratory jar-tests in Canada

4.14.1. Standardised programmes of jar-tests were devised to use American Water Works Association procedures.

4.14.2. Appendix A9 shows the accumulated results from testing raw wastewater from numerous existing operational works using alum, ferric chloride and lime as coagulants. The 95% confidence limits for alum and lime were widely spaced and the 80% removal with lime graph indicates that removal was not dependent on the phosphorus concentration in the raw wastewater. The process is dependent on alkalinity and the pH achieved.

4.14.3. Appendix A10 shows results from testing final effluents from activated-sludge works, using alum and ferric chloride to aid settlement. Although removal was generally good, the correlation of dose with phosphorus concentration in the secondary effluent as the feed liquor was poor, on account of the varying constituents of wastewater. It did not seem practicable to base the control of dosing on the concentration in the feed.

4.15. (c) Results from Operational Works in Canada

4.15.1 The coagulant doses needed to give a final effluent containing 1 mg/l or less of total phosphorus — or to give 80% removals were predicted from jar tests for 14 works of various types and capacities and full scale dosing arrangements were subsequently established on each. Results shown in Appendix A11 indicated that the predictions were good. Coagulant was usually dosed either before the primary settlement stage or into the activated-sludge aeration tank.

4.15.2 Flash-mixing and flocculation were improvised by injecting the coagulant into the raw wastewater pump suction, into the pre-aeration tank, into the flow-measuring flume, or into channels specially provided with mechanical or air agitation. Increasing agitation at the point of application sometimes increased removal markedly. The coagulant dose was generally matched manually to the rate of flow of wastewater and adjusted several times a day.

4.15.3. Pickle liquor containing 20 mg/1 ferrous sulphate was dosed at Chatham, Works 8, to give 83% phosphorus removal, but precipitation did not occur until the ferrous ions had been oxidised to ferric ions. This needed about 0.15 kg 0_2/kg Fe_2 and the reaction required some 2 hours aeration. Thus ferrous iron was not found suitable for removing phosphorus in a primary settlement tank.

4.15.4. Using lime on Works 9-11 gave higher orthophosphate levels in the final effluent than in that from a primary tank probably owing to redissolving the lime flocs carried over into the neutral pH regime in the aeration tank. Cheap and simple arrangements for providing lime treatment at existing works were thought unlikely to produce effluents containing less than 1.5 mg/l phosphorus.

4.15.5. Alum dosing sometimes inhibited nitrification.

4.15.6. When the aeration tank was dosed and the hydraulic loading of the final settlement tank exceeded $35m^3/m^2$ the removal of phosphorus was poor.

4.16. (d) Further Removals

4.16.1. Tertiary treatment processes analagous to those used in water treatment would probably be needed to achieve a level of phosphorus below about 0.5 mg/l and filtration would probably be needed to remove the floc carried over. Iron salts were found not to be suitable coagulants because they coloured the effluent. A high dose of lime would require consequent adjustment of the pH of the effluent.

4.16.2. These Canadian studies also included the removal of phosphorus by treatment in stabilisation ponds, aerated lagoons, and seasonal-retention lagoons, using the coagulants mentioned above.

4.16.3. Related work on phosphorus removal in the Netherlands is reported in paras 6.9.4 and 6.9.5.

4.17. Investigation of substitute chemicals — (a) Introduction

4.17.1 The Canada/Ontario Agreement for Great Lakes Quality required all wastewater treatment works in the watersheds of Lakes Erie and Ontario to remove phosphorus. As large quantities of coagulants would be needed, Environment Canada investigated the feasibility of using certain waste or by-products of local industries. They discussed this with 141 firms in Ontario and Quebec and evaluated materials produced by 48 of them.

4.17.2. During evaluation, degritted raw sewage from the Skyway treatment works at Burlington was settled quiescently in jars in the laboratory. The required effluent standard was 1 mg/l or less of total phosphorus. Appendix A14 gives details and also shows the daily quantities of wastewater that might be treated to the required standard by chemically-aided settlement using the quantities of suitable materials which the survey showed to be available.

4.17.3. Experience suggested that from the wide range of materials available pickle liquors, ferrous sulphate, spent mine acids, carbide lime, stack precipitator and bag house dusts, red muds, and dross from aluminium smelting were all worth further study.

4.18. — (b) Materials investigated

4.18.1. Pickle liquors are the liquid residues from acidic cleansing of ferrous castings and usually contain 30,000-90,000 mg/l ferrous iron, typically in a 10% solution of sulphuric acid. Dosing on an operational scale should present few difficulties as only storage and feeding-systems would be required but there would be a large quantity of free acid. A dose of 30 mg/l — as iron — gave the required effluent quality. Solutions similar to pickle liquors could be produced by the acid dissolution of mill scale which is the oxide material flaking off iron and steel when hammered or rolled.

4.18.2. Ferrous sulphate can be recrystallised from sulphuric acid pickle liquors by cooling under reduced pressure and the supernatant acid could be recovered for recycling. The crystalline ferrous sulphate, which could be dosed either dry or in solution, contains no free acid and might therefore be particularly useful in treating acidic wastewaters. A dose of 20 mg/l — as iron — gave the required effluent quality.

4.18.3. Spent mine acids are the liquid residues from acidic leaching carried out in mineral refining. They may contain about 20,000 mg/l of ferrous iron and several times as much free sulphuric acid as pickle liquors. This inhibits their direct use as a settlement aid. When neutralised or after dissolving further iron in them, a dose of 20-30 mg/l — as iron — gave the required effluent quality. Spent mine acids could also be used in conjunction with carbide lime as noted below.

4.18.4. Carbide lime is a by-product of acetylene manufacture and contains relatively pure calcium carbide. A dose of 400-500 mg/l gave the required effluent quality consistently but the residual lime slurry was abrasive and difficult to pump. A combination of 20 mg/l spent mine acid — as iron — and 200-250 mg/l carbide lime — which reduced pH below neutral — gave effluents containing as little as 0.1 mg/l phosphorus.

4.18.5. Stack precipitator dusts are waste-products of cement manufacture. They are commonly precipitated electrostatically or mechanically and contain about 30% calcium. They removed phosphorus well but about 2,000 mg/l was needed to give the required effluent quality and left a large volume of sludge.

4.18.6. Bag-house dusts are recovered from filtration of air-borne discharges from the steel industry and may be lime-based or iron-based. They behaved similarly to stack precipitator dusts but smaller doses of around 600 mg/l gave the required effluent quality. The iron-based dusts were not as satisfactory as those with a lime base.

4.18.7. Red muds are brick-red sludges containing iron, aluminium, calcium and silica and are the highly alkaline waste-products from the caustic leaching of bauxite ores. They removed phosphorus reasonably well but large doses of around 5000 mg/l were needed to give the required effluent quality. This implied high transport costs and large volumes of sludge. Turbidity was reduced by a supplementary iron dose which also increased phosphorus removal. Small additions of spent mine acid to red mud gave an improved settling characteristic and removal of more phosphorus. A combination of 75 mg/l spent mine acid — as iron — and 2000 mg/l red mud in neutral solution fave an effluent containing only 0.3 mg/l phosphorus, but with a large quantity of sludge.

4.18.8. Red muds may be treated with sulphuric acid and the resulting product can be dried and crushed to a fine powder, by a patent process. This powder with physical properties similar to pulverised lime is called Aluminized Red Mud Solids (ARMS). It can be produced more cheaply than the traditional coagulants. Jar-testing of raw wastewater similar to that referred to above showed that about 200 mg/l ARMS might be needed to give an effluent containing 1 mg/l total phosphorus.

4.18.9. That encouraging result led to small-scale pilot-plant tests at the Wastewater Technology Centre, Burlington incorporating five minutes flash-mixing, forty five minutes flocculation with two tanks in series and settlement in a tank giving two hours retention and an overflow rate of 29.3 m^3/m^2/day. Results compared to those using alum as coagulant on the same pilot plant were:

Parameter			ARMS	Alum
			dose 200 mg/l	dose 200 mg/l
Suspended solids:	feed	mg/l	215	193
	effluent	mg/l	41	21
	removal	%	81	89
BOD_5:	feed	mg/l	174	87
	effluent	mg/l	28	25
	removal	%	84	71
Total P:	feed	mg/l	6.8	6.0
	effluent	mg/l	1.0	0.6
	removal	%	85	90

4.18.10. The average level of dissolved phosphorus in the ARMS effluent was 0.2 mg/l. There were always less heavy metals in the ARMS effluent than in the feed. Doses of 100 mg/l ARMS plus polymer were not so satisfactory as those with 200 mg/l. ARMS produced less sludge than alum and that with an average solids content of 2.5%. Outline cost calculations showed that the market price for ARMS might be 25 dollars/t (1974) giving a chemical operating cost for a phosphorus removal plant of half that for a plant using alum.

4.18.11. Supernatant liquids from leaching the dross from aluminium smelting with acid or alkali and containing 2000 mg/l — 500 mg/l aluminium removed phosphorus well. Appendix A.14 summarises these details.

4.19. Tank Capacity and Design — **(a) Introduction**

4.19.1. Much research has been devoted to the capacity and hydraulic design of wastewater settlement tanks: much was inconclusive and most operational tanks are designed by rule-of-thumb methods deduced from practical experience.

4.19.2. The amount of impurity removed by primary treatment affects the load on the secondary treatment and in any given case the allocation of available resources between the two could be optimised. A model is being developed in the United Kingdom (STOM) to deal with this optimisation of wastewater treatment. Meanwhile practice in providing primary settlement capacity varies widely. A questionnaire circulated to all participating nations during the study elicited the following information:

Country	Detention at maximum daily flow rate, hours
Canada	2.3
The Netherlands	1.0
United Kingdom	2.0
United States	0.5

4.19.3. Using chemicals to aid settlement should reduce the capacity of tank needed. Work in the laboratory and on an operational scale in Canada was aimed at quantifying that advantage and developing a method of predicting it.

4.20. — (b) Results from Canadian Work

4.20.1. The settling characteristics of wastewaters were studied in the laboratory both with and without coagulant chemicals and under quiescent conditions in specially designed columns 0.15m diameter and 2.13m long with sampling ports at 0.3m intervals. At appropriate time intervals samples from the ports were filtered to determine the concentration of suspended solids after various detention times and at various depths. The amount of suspended solids remaining was compared with time and overflow rate.

4.20.2. The following tanks were used in detailed continuous-flow tests:

a. A tank 2.4m diameter x 2.1m side-wall depth, at the Wastewater Technology Centre, Burlington.

b. A tank 40.5m long x 9.0m wide x 2.7m average depth, one of four primary tanks at Sarnia wastewater treatment works.

c. A tank 36m diameter x 3.3m side-wall depth, one of four primary tanks at Windsor wastewater treatment works.

Actual as opposed to theoretical time of retention using dye tracer, settlement rate of floc, velocity profiles, and effect of short-circuiting and dispersion were all measured in the experiments.

4.20.3. The experimenters deduced the performance of primary settlement tanks to be predictable from the formula:

$$S_e = \frac{S_f A}{T^b + A}$$

where S_e = suspended solids in tank effluent (mg/l)
S_f = suspended solids in tank feed (mg/l)
T = actual retention time in tank as determined from tracer studies (minutes)
A, b = constants developed from settling-column tests on the wastewater concerned.

4.20.4. The following values of A and b were found to apply for domestic wastewaters:

	A	b
No chemical added	15.0	0.64
Ferric chloride or alum added	7.5	0.90
Ferric chloride or alum added, plus polymer A-23	3.5	0.93

4.20.5. The overflow rate had little effect within the range studied and was ignored in deducing the formula. Operational constraints did not allow work at overflow rates over 110m³/m²/d, and consequently 100m³/m²/d was recommended as a prudent upper limit for design.

4.20.6. Appendix A.12 shows that the formula gave excellent correlation with measured results.

4.20.7. Appendix A.12 also shows that the actual times of retention measured in the three tanks were often much less than the calculated times, particularly in the circular tanks.

4.20.8. The experiments did not deal with the important question of tank geometry or with type and position of weirs and baffles.

4.20.9. The following tentative guidelines have been suggested for the design of rectangular primary settlement tanks:

Parameter	Guideline
Flow rate to be used in design	Maximum daily flow rate
Actual retention time not to be less than	30 minutes when ferric chloride or alum (plus polymer) are added. 45 minutes without chemicals
Minimum time before 10% of tracer passes outlet weir	15 minutes with chemicals as above 30 minutes without chemicals
Maximum overflow rate not to exceed	100 m³/m²/d under peak flow conditions

4.21. — (c) Opinion in the United States

4.21.1. The following advice has been distilled from a large body of experimental and operational experience in the chemically-aided settlement of wastewaters.

4.21.2. The critical design parameter is thought to be the maximum hourly surface overflow rate, that is the surface overflow rate resulting from the maximum rate of flow in any one-hour period. The maximum rate recommended for both rectangular and circular tanks is 70m³/m²/d, unless pilot-scale work indicates that a higher figure might safely be used. A figure of 45m³/m²/d is the recommended daily flowrate; and whichever of these two criteria results in the larger tank size should be used. US workers pointed out that whilst excess solids are only undesirable in a primary-tank effluent in a biological treatment plant, they might well block the carbon adsorption stage of a physical-chemical plant and cause a complete shut-down.

4.21.3. Tanks using sludge blankets and analogous to those employed in water treatment were unsatisfactory because flow and load variations made the blanket unstable.

4.21.4. Provision should always be made for recirculating controlled quantities of sludge from the base of tanks to the flash-mixing zone.

4.21.5. Suction lines for lime should be glass-lined to aid cleaning, and provision should be made for routine cleaning of all pipelines carrying limed wastewater — possibly with polyurathene swabs. As lime sludges are dense, the tank sludge scrapers should be bottom-scraping rather than vacuum-pickup.

4.22. Neutralisation and Recarbonation — **(a) Neutralisation**

4.22.1. Chemically-aided settlement often results in noticeably acid or alkaline rather than a neutral tank effluent. Appendix A2 shows that using 75 mg/l of ferric sulphate gave an effluent pH of 5.6, and that a dose of 400 mg/l lime gave one of 11.2 at Coleshill.

4.22.2. We stated in paragraph 4.8.5. that such effluents may be undesirable because they may affect adversely receiving waters and subsequent stages of treatment. Limed effluents may form carbonate scale on pipes where the pH is above 8.0 and it may also be desirable to reduce carbonate hardness where re-use of effluents is in mind.

4.22.3. Lime is usually used to raise the pH of acid effluents.

4.22.4. Sulphuric or hydrochloric acids may be added to neutralize alkaline effluents. The reaction is instantaneous and requires relatively little plant. This will increase the concentration of sulphate or chloride ions in the wastewater and the former can lead to attack on concrete surfaces.

4.23. — **(b) Recarbonation**

4.23.1. Paragraph 4.2.6. states that adding lime to wastewater precipitates the natural bicarbonate alkalinity present as calcium carbonate. If enough lime is added magnesium hydroxide also is precipitated. The lime passes into solution as calcium hydroxide.

4.23.2. Carbon dioxide dissolved into the effluent from lime-aided settlement reacts to form carbonate and bicarbonate ions and hence the term recarbonation:

$$CO_2 + 20H \longrightarrow CO_3^{2-} + H_2O$$

$$CO_2 + CO_3^{2-} + H_2O \longrightarrow 2HCO_3$$

4.23.3. Recarbonation may be achieved in a single stage when enough carbon dioxide is added to convert all the calcium hydroxide to the bicarbonate. Using the Langelier Saturation Index it is possible to ensure reaching a final pH low enough to prevent calcium carbonate scale forming — generally below pH 8.0. Carbon dioxide can be dissolved by coarse-bubble diffusion from a depth of about 2.5m, or by mechanical agitation in an enclosed bell to give about 15 minutes reaction time. The resulting effluent will have a relatively high calcium bicarbonate content and high alkalinity.

4.23.4. Two-stage recarbonation is a modified process to reduce bicarbonate alkalinity and carbon dioxide consumption and it may enable recovery of some lime from calcining the sludge produced. The pH is first reduced to 9.3 to ensure the carbon dioxide being present as the carbonate ion. Calcium carbonate being relatively insoluble is precipitated and can be settled-out. The effluent from that settlement is recarbonated in a second stage to neutral pH with residual carbonate then redissolving as the bicarbonate. Removing calcium carbonate reduces the calcium content and alkalinity of the final effluent and also reduces the carbon dioxide demand in the second recarbonation stage.

4.23.5. However, the two-stage process has two particular disadvantages: the precipitated carbonate forms a tenacious scale on exposed surfaces, and settlement can be poor as some of the precipitate is semi-colloidal. Recirculating the carbonate sludge to the first-stage vessel partly overcomes both of these problems. This technique provides a crystal seed which increases crystal size and thus reduces the proportion of carbonate crystallised on surfaces. Seeding also increases the rate of reaction. As precipitation rate is controlled by seed crystal mass, increased seeding results in a more rapid reaction.

4.23.6. Carbon dioxide can be imported as a liquid, or generated on site by combustion of fuel oil and of liquified petroleum gas. Both methods are expensive. Carbon dioxide from the flue gas from site incineration or recalcination of sludge can be used after scrubbing and compression.

4.23.7. The following are some recarbonation results from the Coleshill pilot plant:

parameter (mg/1 except for pH)	Effluents from		
	Lime-aided settlement	Settlement after first-stage recarbonation	Sand filtration following recarbonation
pH	11.3	9.1	7.1
Suspended solids	42	42	9
BOD_5	106	78	78
COD	183	166	129
TOC (total)	57	52	36
TOC (dissolved)	52	49	31

4.23.8. Removal of some organic matter was evident. Little calcium carbonate sludge was produced, due probably to organic molecules binding the calcium and preventing precipitation.

4.23.9. Recovering and recalcining calcium carbonate sludge seems unlikely to be economic when treating high-strength wastewaters.

4.23.10. Appendix A13 records initial experience with recarbonation at the Coleshill pilot plant.

4.24. The treatment and disposal of sludges — (a) General

4.24.1. The advanced treatment systems designed to produce effluents of normal quality using chemical aids and those removing phosphorus and/or nitrogen must from their very nature generate sludges having more solids and a different composition than those from a traditional works. These sludges will be of different treatability. Future wastewater treatment plants designed to produce effluents of substantially higher quality than can be obtained by traditional primary or secondary processes may generate still more sludge problems.

4.24.2. Chemically-aided settlement usually comprises coagulation, flocculation, and thus enhanced settlement of suspended and colloidal particles by using iron, aluminium or calcium compounds. These aids add substantially to the quantity of sludge which must be removed, increases of 30% to 40% being typical. With the exception of lime they tend to have a detrimental effect on the dewatering and other characteristics of the chemical sludge compared with those of sludge discharged from more normal treatment works; greater quantities of thicker and sometimes gelatinous sludge are produced at higher pH values.

4.24.3. Most of the lime used is precipitated as calcium carbonate and the amount of new lime required in the system can be reduced by recovering and re-using the precipitated calcium carbonate. Recovering lime from combined sludge has problems from the many other constituents precipitated with the calcium carbonate which if not separated would be returned to the plant, build up, and may then affect the process adversely. Lime sludge may be disposed of by incinerating the waste solids with separate recalcination of the calcium carbonate, by incinerating the whole sludge with integral recalcination and lime re-use, or by disposing in landfill following digestion of the organic solids. The incineration — recalcination treatments are designed to reduce the cost of chemicals used and the quantity of solids for final disposal.

4.24.4. Calcium sludges are alkaline and when applied to land reduce the uptake of metals by crops; iron and aluminium sludges however tend to be acid and do not reduce this uptake significantly. Crop yields increase with increasing rates of application of lime sludges but decrease with aluminium sludges indicating that the latter may have some toxic effects. Using sludges at moderate rates will be unlikely to cause serious deficiencies or any toxicity from boron.

4.24.5. Analyses of sludges in Canada have shown significant differences in nutrient, heavy metal, pesticide and microbial concentration levels in sludges from works practising phosphorus removal with alum, ferric chloride or lime as precipitating agents. These variations within the results from individual plants could be random, could be long term trends or could stem from variations in raw sewage quality or the treatment plant operation.

4.24.6. The metals in the coagulants used for phosphorus precipitation occur naturally and their disposal should not present much of a problem. Phosphorus is required frequently as a nutrient and the effects on nitrogen availability and sludge decomposition are concluded to be more important than the direct presence of the elements. The high concentration of aluminium and iron in sludge may accelerate toxicity in plants and the soil and lead to nutrient deficiencies. Any smaller crop response from application of aluminium sludges may result from the less nitrogen available.

4.24.7. Chemically treating wastewater to remove phosphorus does not seem to have much affected the use of the sludge on agricultural land.

4.24.8. In Canada it has been shown that metals can be extracted readily from sludge and that recycling iron and phosphate is profitable. In soils in Ontario the phosphorus in calcium sludge appears to be appreciably more available than that in iron or aluminium sludges and this could be a disadvantage.

4.24.9. The Zimpro sludge heat treatment process is particularly suitable for conditioning sludges that are not amenable to anaerobic digestion. Using high pressure air and steam, the process converts the sludge to a sterile and stable residue. Water separates readily from the conditioned sludge without further chemical aid. The process gives off an unpleasant odour that may require removal by for example a scrubber.

4.24.10. During the summer of 1976 tests showed the primary sludge from the pilot plant at Coleshill to have markedly superior filtration properties to those encountered in normal primary sludges, and that it contained more large particles. Sludge from settlement of sewage abstracted at the pilot-plant intake was compared with that produced at the main works at Coleshill. This was done using a crude form of particle-size analysis and by measuring capillary suction time (CST), loss on ignition (LOI) and specific resistance to filtration (SRF).

4.24.11. Adding return liquors to the sewage changed the sludge propeties markedly making them more like primary sludges from traditional plants. Nevertheless a survey of works where no liquors were returned showed that most of the sludge examined differed in particle size distribution from the Coleshill primary sludge.

4.24.12. The exact reason for the atypical nature of the sludge from the Coleshill plant is not clear. As we do not think the settled sewage is atypical we may have to accept at this early stage that our conclusions from studies of sludge properties must be general rather than precise.

4.24.13. Investigation confirmed the sieve test as reproducible with only small variations between operators. The sieve analysis of sludge from a continuously scraped sedimentation tank was similar to that from an unscraped tank and thus the atypicality probably did not result from continuous scraping leading to an agglomeration of fibrous materials.

4.25. — (b) Quantity, quality and filter pressing

4.25.1. We have reported examples of the increased yields of sludge from chemically-aided settlement in the United Kingdom and of the characteristics of the sludges and we have drawn attention to the increased dose and sludge yield applying to high-alkalinity wastewaters when lime was used.

4.25.2. Other figures for yields of chemical sludges were obtained during an extensive survey of operational works in Ontrario, many of which had been provided with chemically-aided settlement for phosphorus removal under the Great Lakes Agreement. Analysis of data obtained led to the following generalised sludge production figures being recommended as design criteria for Canadian plants:

Works type	Estimated probable sludge production		
	m^3/person/d	volume as % of dwf*	kg/m^3 wastewater
Conventional primary settlement	.35	0.20	0.12
Chemically-aided primary settlement (metal salts)	.50	0.32	0.17
Conventional activated-sludge	.52	0.38	0.17
Activated-sludge fed from chemically-aided primary settlement (metal salts)	.64	0.51	0.22

*average dry-weather flow of wastewater

Most chemically-aided settlement works in Ontario were aiming at effluents with not more than 1 mg/l total phosphorus — as P. These chemical sludge production figures are strikingly less than those reported from experimental work in the United Kingdom but it should be borne in mind that our wastewaters are generally 'stronger' and we aim at maximising removal of impurities other than phosphorus.

4.25.3. In the United Kingdom we found that sludge from lime-aided settlement — 'lime sludge' — generally consolidated well when simply settled by the process commonly used for thin sludges derived from the conventional unaided settlement of wastewater. Some results from the United Kingdom are:

Wastewater limed to pH	Consolidation time (d)	Sludge production (kg/m^3 wastewater)	Dry solids %		% Increase in dry solids
			Into contanks	Out of contanks	
11.4	3	0.76	3.80	4.48	18
11.4	7	0.72	4.47	6.93	18
11.0	6	0.56	4.99	7.73	54
11.0	3	0.66	5.14	7.89	53
10.5	4	0.48	5.76	6.36	54

4.25.4. Lime sludges in the United States thickened to 10-25% dry solids by consolidating, and Norwegian work reported 6-15% dry solids after consolidating for one day only.

4.25.5. Neither alum nor iron sludges consolidated well. The United States reported 2.5% dry solids for both whilst Norway reported 1.2-4.0% dry solids for iron and as little as 0.5-2% dry solids for alum sludges after consolidating for one day.

4.25.6. Our Coleshill plant produces sufficient sludge to enable full-scale filter-pressing. Whilst sludges from conventional unaided settlement of wastewater need conditioning with coagulant chemicals before pressing the following Coleshill figures show that this may not be necessary for lime sludges:

Serial	Wastewater limed to pH	Consolidation time (d)	Dry solids %	
			Into press	Out of press
1	11.4	3	5.9	36
2	11.4	7	7.5	36
3	11.0	3	7.7	36
4	11.0	6	8.1	33
5	10.5	4	9.9	42

Pressing time was 7 hours at 828 kPa (120 lb/in^2) including time to reach pressure. Cloths became progressively dirtier between serials 1-4, and other pressings not recorded above were performed between each serial. There were 22 pressings before the cloths were cleaned immediately before serial 5. Specific resistance to filtration (SRF) ranged from 36 to 66. Laboratory work showed the dried sludges could be imrpoved markedly by conditioning with small doses of anionic and cationic polyelectrolytes, the former being particularly effective.

4.25.7. Experience in the united States showed that lime sludges could be dewatered to 20-40% dry solids. Corresponding figures for iron and alum sludges were only about 10-20%. Opinion in the United Kingdom was that iron and alum sludges needed chemical conditioning before they could be pressed effectively.

4.25.8. Capillary suction time (CST) tests were performed on conventional and lime sludges derived from Davyhulme's variable and highly-industrialised wastewater as a first step towards evaluating dewatering characteristics. Appendix A15 shows results including those for primary sludges and for surplus sludges derived from activated-sludge treatment of limed and unlimed wastewater.

4.25.9. Appendix A15 shows capillary suction times for surplus activated sludges from Davyhulme, before and after liming the raw wastewater concerned.

4.26. — (c) Anaerobic Digestion

4.26.1. Our Canadian co-pilots studied anaerobic sludge digestion on full scale at Newmarket works, Ontario, before and after adopting lime-aided primary settlement for removing phosphorus. Newmarket was an otherwise traditional 9000 m^3/d activated-sludge works treating domestic wastewater; surplus activated sludge and supernatant liquor from the digester were returned to the incoming wastewater. Digested sludge was disposed of to farmland.

4.26.2. During lime-aided settlement 200 mg/l lime, as $Ca(OH)_2$, was dosed upstream of the two primary settlement tanks. Raw sludge from one tank was recycled to the flash-mixer and from the other was pumped to digestion. The covered primary digester had a capacity of 850m^3 with gas-recirculation to its base and the open secondary digester had a capacity of about 900 m^3. The primary digester was heated to about 95°F (35°C) by heat-exchange with a boiler fuelled by either digester gas or oil.

4.26.3. Data before and during the trials are shown in the table on page 50.

4.26.3 Effect of lime-aided settlement on Anaerobic Digestion

Parameter	Before liming of wastewater (1970 data)	During liming of wastewater (1972-73 data) 200 mg/l $Ca(OH)_2$
WASTEWATER		
DWF	7100m^3	8300m^3
average suspended solids (mg/l)	198	360
BOD_5	(note 1)	(note 1)
pH	—	(note 2)
RAW SLUDGE		
% dry solids	3.4	9.4
% volatile	62	28
kg dry solids/m^3 wastewater	0.17	0.54
litres/1000m^3 wastewater	4900	5730
DIGESTED SLUDGE		
% dry solids	3.3	10.2
% volatile	56	24
kg dry solids/m^3 wastewater	0.12	0.46
litres/1000m^3 wastewater	3600	4600
DIGESTER SUPERNATANT		
% dry solids	0.7	1.2
% volatile	—	24
soluble phosphorous (mg/l as P)	150	4
PRIMARY DIGESTER LOADING		
kg volatile solids/m^3 d	0.983	1.667
DIGESTER GAS		
m^3/d	—	421
m^3/kg volatiles destroyed	—	2.2 (note 3)
% CO_2: % CH_4	23:73	21:72
VOLATILE SOLIDS REDUCTION		
%	22 (note 4)	37 (note 5)

Notes:
1. Average design BOD_5 231 mg/l.
2. About 0.6m sludge was allowed to build-up in the primary settlement tank such that pH of sludge to digester was about 9.4.
3. During the last month of the Study.
4. Using standard equation.
5. From mass balance.

4.26.4. Some but not all the increased sludge solids during liming were attributable to a higher suspended solids content in the wastewater. The secondary digester stratified and the total digested solids varied from 3% to 28%. The soluble phosphorus in the supernatant liquor from the digester was reduced strikingly and the gas was of good quality. Lime sludge pH stabilised at about 7.2, at a value suitable for disposal to cropped land; a lower figure would have increased solubility of heavy metals. The digested lime sludge contained about 1.4% total phosphorus and 1.8% total nitrogen; cropping improved on land to which it was applied.

4.26.5. When assessing the effects of dosing alum on an operational activated-sludge works at Guelph, Ontario, (para 4.26.6.) operating difficulties supervened to prevent evaluation of its effects on the anaerobic digestion practised at the works. Instead, sludge production was monitored qualitatively. Representative samples of each mixed sludge were collected for one month from the respective primary settlement tanks to which surplus activated-sludges were returned in the normal way and given bench-scale anaerobic digestion.

4.26.6. Average total dry solids figures for the waste sludges sampled were:

Works operating at	Sludges from	
	Alum plant % dry solids	Control plant % dry solids
Design capacity	3.4	3.0
25% overload	5.2	4.7

Alum plant sludges were gelatinous and their significantly increased dry-solids were inferred as due largely to the contained inorganic aluminium solids for the control plant sludges, had higher volatile content (72% as against 63%). None of the sludges settled well and the alum plant sludges showed signs of bulking. In each case the entire sludge mass-settled as a blanket. Appendix A16 illustrates settlement rates.

4.26.7. The pH values and alkalinities of the alum plant sludges were normal at 6.5-6.7 and 2900-4100 mg/l respectively but volatile acid contents were high at 1290 to 2010 mg/l. Chemical degradability as indicated by COD was roughly similar for the sludge from both the control plant and the alum plant. Concentrations of total organic nitrogen were higher for control at 1160 mg/l than for alum plant sludges at 1085 mg/l, due to the higher inorganic factions in the latter. Although free ammonia produced by denitrification during the 4-10 days closed storage was 200 mg/l for control and 240 mg/l for alum plant sludges, the latter result did not necessarily imply easier degradability. Phosphates were slightly but significantly higher in alum sludges.

4.26.8. Anaerobic digestion was carried out for a month in 2 litre digesters operated in parallel. Gas production on the first day was good indicating that the sludges had not been upset by transportation. Each digester was batch-loaded initially averaging 1.6 kg BOD_5/m^3/day (0.1 lb/ft^3/d) and later at twice that rate, which doubled gas-production in each digester. Both digesters adapted easily to the high volatile acids in the sludges. The pH values of digester contents fell only slightly to 7.7-7.3 and alkalinities remained high. Suspended solids did not increase during digester operation indicating that digestion was proceeding normally.

4.26.9. The study demonstrated that alum plant sludges were as amenable to anaerobic digestion as control plant sludges.

4.26.10. Vacuum filtering and centrifuging of undigested control and alum sludges showed that the latter filtered better giving a cake of 88% moisture content after 1h filtration, as against 86% for control, but centrifuged less well with only 76% liquid removed after 5 minutes, as against 82% for control.

4.27. — (d) Aerobic Digestion

4.27.1. Bench-scale work in the laboratory was carried out at 20°C on the completely-mixed aerobic digestion of primary and surplus activated sludges from a works in Toronto employing both conventional and lime-aided settlement, the latter at doses of 140-600 mg/l giving pH values between 9 and 12. All sludge studies had similar initial volatile content. Batch and semi-continuous daily feed experiments were made with detention times in the digester from 7 to 15 days.

4.27.2. Aerobic digestion of lime sludges was feasible but a minimum of 15 days aeration at 20°C was needed, particularly for sludges with high pH values.

4.27.3. Process-kinetics for sludges with initial pH values from 9-10 were higher than for control sludges; but for those with initial pH values from 10-12 they were lower, owing to high alkalinity/calcium content. Nitrification, normally a feature of aerobic digestion, was inhibited.

4.27.4. Soluble phosphorus in the control supernatant reached 28-40 mg/l after digesting for 28 days but was only 3-5 mg/l for the lime sludge.

4.27.5. The specific resistance to filtration achieved in primary sludges during semi-continuous aerobic digestion experiments, all results (apart from pH) being expressed as sec^2/g x 10^7 were:

Control sludge		Limed sludge				
Feed sludge	Digested sludge	pH of feed sludge	Feed sludge	Digested sludge after digestion for:		
				7d	10d	15d
1375	180	9.5-10	64	21	33	60
1106	182	10.5-11	27	12	11	17
1039	139	11.5.12	12	16	24	24

4.27.6. Laboratory bench-scale work was done in Norway on aerobically digesting sludge from conventional primary settlement, and on mixtures of sludges derived from conventional primary settlement and alum-aided secondary settlement. Twenty continuous digestion units were operated in parallel with detention times of 5, 10, 15, 25 and 35 days and at temperatures of 7, 12, 18 and 25°C.

4.27.7. Appendix A17 shows the effects of detention time on degradation of organics in the sludge. Supernatant liquors had low biochemical oxygen demand and phosphorus content. The mixed primary/alum sludges released no phosphates to the supernatant liquor when stored anaerobically.

4.27.8. Aerobic digestion improved sludge dewatering and filtration and seemed to work well in general.

4.27.9. Operational experience in Sweden showed that chemical sludges were amenable to mechanical dewatering by filtration and centrifugung.

4.28. — (e) Canadian Lysimeter Studies

4.28.1. Disposing sludge derived from chemically-aided settlement on to land could contaminate water, soil and plants. Since 1972, to complement field investigations, the Wastewater Technology Centre at Burlington conducted lysimeter studies on sludge application using two typical Ontario soils, a loamy sand and a silty loam.

4.28.2. Sixty-six lysimeters each 0.3 m diameter and 1.8 m deep were used as soil containers. Winter temperature was maintained at about 4°C and summer temperature was ambient. Thirteen seedlings of orchard grass, Frode variety *Dactylis glomerata* chosen for its hardy and adaptable nature and grown in sterilised soil, were planted in each lysimeter.

4.28.3. Anaerobically digested sludge from operational works using an iron salt, alum and lime as coagulant was applied to the lysimeters at rates of 100, 200 and 300 kg Total Kjeldhal Nitrogen/hectare (TKN/ha) on three occasions in 1973 and four in 1974. Control lysimeters with no sludge applied and commercial fertilizer lysimeters with Nitrogen, Phosphorus and Potassium (NPK) applied were used with each soil. The crops of orchard grass were cut four times during each growing season, rinsed, dried, ground, weighed and analysed chemically.

4.28.4. The yields of the orchard grass crop in 1972 and 1973 as tonnes dry matter/hectare were:

Treatment	1973			1974		
	kg TKN/ha (total)	Loamy sand	Silt loam	kg TKN/ha (total)	Loamy sand	Silt loam
Control	0	4.3	8.4	0	2.5	5.3
NPK	336/112/112	12.9	13.2	400/133/133	12.7	15.2
Alum)	300	5.1	8.8	400	7.9	10.9
Sludge)	600	5.8	9.6	800	12.1	16.1
)	900	7.1	10.2	1200	14.1	18.7
Iron)	300	7.1	11.2	400	7.8	11.2
Sludge)	600	8.8	12.6	800	11.9	14.5
)	900	11.6	15.2	1200	15.4	20.5
Lime)	300	6.2	11.1	400	5.8	10.5
Sludge)	600	8.6	12.7	800	10.5	14.2
)	900	10.6	14.4	1200	13.2	17.0

4.28.5. No significant interaction between soil type and treatment was noted. The differences in yield for all other variables (Control v. Others, NPK v. Sludge, Sludge type, Sludge rate, and Sludge type v. Rate) were significant at 0.01 probability, except for the 1974 Sludge type v. rate for which the figure was 0.05. Yields from both soils increased with increasing application for all types of sludge. Although nitrogen-stimulated potassium deficiency, particularly at high applications, may have limited yields in 1974, those yields were generally higher than in 1973. The highest rate of application of iron and lime sludge produced a higher yield on both soils than did NPK. Yields were higher than would be expected under normal field conditions because:

a. The forage overhanging from the lysimeters increased the area exposed to light.

b. Ample moisture was always available.

c. Manual harvesting minimised loss of plant material.

4.28.6. The iron and lime sludges used were derived from the same works during both experimental years but the alum sludges were from different works. The limited crop yield from alum sludge in 1973 was attributed to its total lipid (petroleum hydrocarbon) concentration of 6200 mg/l, the corresponding figure in 1974 being only 150 mg/l. Orchard grass from 1973 alum sludge showed intense yellowing by the fourth cut which could indicate hydrocarbon toxicity.

4.28.7. Nitrogen, phosphorus, potassium, calcium, magnesium, sodium, iron, manganese, aluminium, copper, zinc, nickel, chromium. lead and cadmium concentrations in the grass were compared with normal ranges quoted in the literature. No toxic effects were found for any constituent. Potassium was low in 1973, extremely so in 1974. Iron from iron sludges was higher than normal but control sludges were also high. Aluminium in 1973 was above normal on loamy sand. Lead from iron sludges was a little higher than normal. Nitrogen uptake increased with increased sludge applications. Phosphorus concentrations in 1974 were adequate for orchard grass. Potassium deficiencies were observed in 1974.

4.28.8. Nitrate-Nitrogen, Calcium and Chlorine in leachates from both soils were high in the 1973 growing season and declined thereafter. Nitrate-nitrogen was less than the drinking-water standard of 10 mg/l (Canada, 1969) maximum during the dormant season and 1974 growing season for all treatments. The total organic carbon did not exceed 15 mg/l in 1973 but increased substantially in 1974. Total phosphorus was generally under 0.2 mg/l. Calcium, Magnesium, Iron, Copper and Zinc were within drinking-water limits (Canada, 1969), while Chloride, Nitrogen, Manganese, Nickel, Chromium, Lead and Cadmium were within irrigation water limits. Zinc, Copper, Chromium, Lead, Nickel and Cadmium were negligible. Leachate Nitrogen and Calcium losses were higher from loamy sand than from silty loam.

4.28.9. Heterotrophic bacteria in the leachate identified as originating in the soil ranged from 0.1 to 5.5 x 10^6/ml. The sludge micro-organisms were retained in the top 15 cm soil layer, although no coliform bacteria were observed below 7.5 cm.

4.28.10. Soil profiles were not disturbed to avoid destroying the grass roots but the soil horizons will need sampling sometime to compare calculated and actual material balances.

4.28.11. The highest calculated depletion of Nitrogen, Phosphorus, Aluminium, and Potassium from both soils occurred at the high rate of application of alum sludge. The highest accumulation of Iron, Zinc, Copper, Chromium, Lead and Cadmium occurred at the high rate of application of iron sludge. The high rates of application of alum, iron and lime sludge resulted in the highest accumulation of Aluminium, Iron and Calcium respectively in both soils. The long-term effects of accumulations of heavy metal in soils at current rates of application remain to be determined.

4.28.12. Cadmium was the heavy metal of greatest concern. All types of sludge used would double the initial soil content of Cadmium in less than one year at the highest rate of application. The relationship between cumulative total and plant-available Cadmium loadings and actual concentrations of Cadmium in plant tissue remain to be determined.

4.29. — (f) Land Disposal in Canada

4.29.1. The Canadian work with chemical sludges already referred to formed part of a comprehensive research and development project resulting from the Great Lakes Agreement under which most wastewater treatment works in Ontario were provided with phosphorus-removal facilities.

4.29.2. As some form of chemically-aided settlement was likely to be the best way of removing phosphorus, there was concern that the resultant sludges containing relatively high concentrations of heavy metals and other substances potentially harmful to plants would be acceptable agriculturally. There was also concern about their effects on surface-water runoff and on sub-surface seepage. More than 50,000 tonnes of sludge a year, over a third of the total production of Ontario works, was being disposed of to land without difficulty.

4.29.3. Pending the results of extensive investigatory work, interim guidelines for land disposal of chemical sludges were issued in Canada covering site location and management, application rates, and hauling and spreading equipment. The study included characterisation of chemical sludges and described laboratory, lysimeter, greenhouse and field scale trails on the effects on cropping, crop content, soils and runoff, and of applying various chemical sludges to various soil types. The effects of land-slope were also studied. Work is still in progress.

4.29.4. The sludges used for these experiemnts were from operational works giving primary chemically-aided settlement and chemically-aided settlement associated with activated sludge treatment. The chemical coagulants used were lime, ferric chloride and alum.

4. 29.5. Outline indications from laboratory, greenhouse and field-scale work reported in 1977 are given below but in the space available we cannot deal adequately with this exhaustive and important project. We draw attention to the references given.

4.29.6. A group of sludges with various metal contents was used in greenhouse studies to develop suitable extractants for plant-available cadmium, copper, nickel, lead and zinc.

4.29.7. In another series of studies nine liquid sludges selected for their high metal content were applied to soils previously adjusted to two pH levels. Five crops of rye grass were grown after applying the sludge. Increased levels of sludge application increased metal levels in the ryegrass, but repeated application/cropping cycles did not increase plant metal content from one crop to the next.

4.29.8. Using Swiss chard (a type of beet), plant-available cadmium, nickel and zinc could be predicted using several extractants of which nitrilotriacetic acid was probably the most acceptable; prediction was more accurate when soil pH, clay content, organic matter and cation exchange capacity were measured. Microscopic investigation indicated surface accumulations in greenhouse soils to be mixtures of salt evaporates and micro-organisms.

4.29.9. During field studies, brome (a large genus of grass with dropping spikelets) was grown on loam, and stover corn (a fodder plant) and grain corn were grown on loam, sandy loam and clay loam.

4.29.10. Brome gave slightly higher crop-yields following application of sludge than from sodium nitrate. Corn yields were little affected by sludge or nitrogen. Low-rate applications of lime sludges tended to give lower cropping rates than similar applications of other sludges; high applications tended to give higher rates. Sludge — particularly lime sludge — markedly increased sodium bicarbonate-extractable plant-available soil phosphorus. Phosphorus concentrations in crops were high but unaffected by treatment.

4.29.11. Sludge application increased the cadmium content of brome and stover corn. Nickel, chromium and copper were increased in some plant tissues on some sites but the effects were inconsistent. Zinc increased in brome and corn grain and at one site on stover corn. Plant-tissue molybdenum appeared to increase with sludge application.

4.29.12. In 1973-75 salmonella species were detected in 20 of 54 samples of sludge, in 1 of 484 samples of runoff water, in 2 of 96 samples of grass, and in 4 of 24 samples of corns.

4.29.13. In general the average ammoniacal nitrogent content of sludges studied was 1.3% on dry weight or 27% of the total nitrogen. In two experiments 40% and 48% of the ammoniacal nitrogen was lost from sludge applied to the soil surface by volatilisation occurring in five and eight days respectively.

4.29.14. Soil salinity was not a problem in the field under Ontario conditions, but could be serious in less humid areas. Boron levels in some sludges tested could pose a problem in arid regions.

4.29.15. Large amounts of metals were added to soils by some sludges; removal by crop uptake or leaching was very limited.

4.29.16. The organic nitrogen in sludges was mineralised gradually, the rate varying from one sludge to another. As with other sources of nitrogen, applications in excess of crop requirements led to high levels of nitrate in solution in the soil.

4.29.17. Sludges supplied nitrogen and phosphorus for crop production but little potassium. They produced high crop yields as did chemical fertilisers, but at least 200% of NPK nitrogen rates were needed from fluid sludge for equivalent yields.

4.29.18. The heavy metals Cadmium, Chromium, Copper, Nickel, Lead and Zinc did not exceed suggested maximum 'tolerance' or 'toxic' concentrations in orchard grass or wheat crops (mean of all sludges 1973-1976).

4.29.19. Salmonellae were isolated from only five out of 207 plant samples tested. If vegetables are not grown and animals not grazed on areas receiving sludge and if reasonable care is exercised in spreading, sludge should not pose a serious health hazard through the crops grown.

4.29.20. Applying sludge did not markedly increase nutrients, heavy metals or bacteria in runoff on 2% and 6% slopes except when heavy rain followed immediately.

4.29.21. Maximum concentrations of Cadmium, Chromium, Copper, Nickel, Lead and Zinc in leachate did not exceed Canadian drinking water standards. Soluble Phosphorus in the leachate from NPK and liquid sludge treatments ranged as high as 10 mg/l during summer 1977. Soluble Phosphorus from the air-dried sludge experiment remained low. The Total Organic Carbon in leachate from both experiments increased to over 50 mg/l in 1976 at the highest sludge loading sites. Static bioassay toxicity tests using Daphnia showed no toxicity in samples of leachate having high Total Organic Carbon values.

4.30. Filtration

4.30.1. Filtration removes particulate matter from a fluid. Two types of process are commonly used; surface filters and in-depth filters.

4.30.2. Surface filters rely on removing solid matter at the water/filtration-medium interface. Examples are microscreens and slow or rapid sand filters. They have been used successfully to provide potable water but have rarely been associated with physical-chemical treatment of wastewater.

4.30.3. In-depth filters rely on collecting the solids throughout their depth and are used extensively in physical-chemical systems either preceding granular activated carbon adsorption or following powdered activated carbon treatment.

4.30.4. An in-depth filter should have a gradual variation in media size from the top to the bottom with the largest on top where the wastewater is applied. However back-washing would disrupt the grading and providing a grid at the top of the filter does not overcome this. The most common type of in-depth filter consists of two or more layers of different density media with the largest granule size but the lowest density on top and a corresponding size/density variation in the lower layers. Three layers are often used — the top layer of anthracite (specific gravity 1.35-1.75), the second layer of silica sand (specific gravity 2.65) and the third of garnet sand (specific gravity 4-4.2). The USA Environmental Protection Agency has detailed the considerations in the selection of media. It recommends allowing for a small degree of intermixing at the interface between layers by careful selection of media sizes and rates of backwash. The minimum depths of media should be 400-500 mm for anthracite coal and 300-400 mm for silica sand.

4.30.5. A third type of filter uses a deep bed of coarse sand giving a slightly poorer quality filtrate but longer intervals between backwashing. This type is not used widely in physical-chemical treatment.

4.30.6. The frequency of backwashing depends on the liquid being filtered, on the performance required of the filter, on the media, and on the efficiency of the backwash itself. Procedures were evaluated by the Environmental Protection Agency in 1977 who concluded:

a. Air scour is essential to release solids from the media before the start of the backwash.

b. Dual and triple media filters must have sufficient backwash to fluidise the bed effectively, to remove solids and to permit ultimate restratification of layers.

c. Previously filtered rather than influent water should be used for backwashing.

4.30.7. Biologically treated effluents and those containing higher dissolved pollutant levels in chemically clarified wastewater may generate biological growth on filter media and therefore may affect backwashing significantly.

4.30.8. Little information has been published on the performance of filters used in physical-chemical treatment. Appendix A18/1 gives results from plants in South Tahoe, California, and Blue Plains, Washington, United States and Coleshill, United Kingdom. Comparison of results from the two countries is difficult primarily because of the widely different strengths of filter influent.

4.30.9. The Environmental Protection Agency recommends that all installations should be provided with means for adding polyelectrolytes. These are available at the Coleshill plant although they have not been tried yet.

4.30.10. At Coleshill with three pressure filters containing 0.8 m depth of anthracite on top of 0.8 m of sand, backwash was difficult. Adjusting the time of air scour to allow simultaneous flow of air and backwash water, prior to the onset of backwash water overflow from the top of the columns overcame this. Such a filtration stage may not be an essential part of a granular carbon treatment process as carbon columns alone have been used successfully at Pomona, California, for combined filtration and adsorption.

4.30.11. Filtration is an essential part of the powdered activated carbon treatment process as it is the last liquid-solids separation stage for producing consistently a highly clarified effluent. Experimental work at Salt Lake City, Utah, indicated that using too-fine a coal media resulted in little penetration of solids into the bed necessitating more frequent and excessive backwashing. Later trails with a tri-media filter removed consistently over 70% suspended solids from an influent with suspended solids up to 100 mg/1. Adding polyelectrolyte to the chemical treatment or direct to the filter influent produced effluents with a suspended solids content below 8 mg/1. This work led to the Environmental Protection Agency recommendation for a peak load design of 9.75 $m^3/m^2/h$ and also highlighted the importance of air scour in the backwash procedure.

4.30.12. France has developed a process having many of the attributes of both media filtration and activated-carbon adsorption and can use direct oxygen application. They observed that the biological activity which develops in media filtration and carbon adsorption is often disadvantageous but can under certain conditions be turned to good account, being used to help reduce biochemical oxygen demand. In media-filters one of those conditions ensured that backwashing, although efficient, would not curtail or inhibit any beneficial biological action occurring in the media. 'Biolite' filtration should make it possible to achieve this double aim.

4.30.13. The 'Biolite' grains are cylinders of expanded clay 2-3 mm in diameter and 4-5 mm long. Their open macroporosity enables them to support biological micro-organisms and their bulk density of 0.5 facilitates bed-expansion when backwashing.

4.30.14. One process-mode involves pre-aerating the feed, which is normally effluent from secondary biological treatment or from chemically-aided settlement, before passing it downwards through the filter which need not be totally enclosed. Biological micro-organisms develop which utilise the oxygen in the aerated feed and the resulting effluents have a significantly lower biochemical oxygen demand than would be obtained by ordinary media filtration. In time the bacterial mass in the filter reduces flowrates and counter-current backwashing is carried out with simultaneous injection of air. Biological activity is not seriously impaired even by intense rates of backwashing owing to the ability of 'Biolite' to support and contain micro-organisms. Under normal conditions the amount of oxygen that can be dissolved in the feed is limited to perhaps 8 mg/l. Clearly any increased oxygen availability would increase the oxidation potential of the 'Biolite' mass and reduce the danger of sulphide development with its attendant smell nuisance. This can be done by recycling filtered water to the aeration stage, or by using 'pure' oxygen, which implies a closed filter.

4.30.15. The second process-mode — 'Biolite' filtration aided by 'pure' oxygen — can reduce biochemical oxygen demands by 60-70% at heavy loadings of say 10 kg $BOD_5/m^3/d$ to 20 kg $BOD_5/m^3/d$. It is used best for treating feeds relatively low in suspended solids of say under 30 mg/l but having high levels of BOD_5 of 40 mg/l to 100 mg/l. A particularly attractive application of oxygenated 'Biolite' filtration is following chemically-aided settlement to deal with rapidly fluctuating loads from holiday resorts. This combination, patented under the name of 'Flopac', can be brought into full operation in a few hours and consumes chemicals and power in more-or-less direct proportion to the incoming load. An installation of this type is to be provided at Briancon wastewater treatment works in France where chemically-aided flotation will precede the oxygenated 'Biolite' stage.

4.31. Activated Carbon Adsorption — (a) General

4.31.1. Activated carbon is used in wastewater treatment to remove dissolved pollutants remaining after previous treatment — mostly after chemically-aided settlement. The effectiveness of a particular activated carbon is related to the pore size distribution which affects transport within the carbon, the total surface area and the surface activity.

4.31.2. The most important factors in designing any adsorption system are carbon dosage and loading, mode of operation, and contact time with the wastewater. Achievable loadings can be assessed by reviewing the quantity adsorbed by any particular material against its concentration in the wastewater. Increasing contact time with wastewater will generally increase organic saturation of the carbon thus reducing both the carbon dosage required and the cost of regeneration. To reduce cost the contact time must be optimised, probably by developing a kinetic model.

4.31.3. Two different activated carbon processes are used in wastewater treatment, one using granular and one using powdered carbon. They are divided simply on the size of carbon particle used. Granular particles are generally about 0.4 to 0.2 mm diameter whilst those in powders are less than 0.1 mm diameter. Whilst the principles of adsorption remain the same, different equipment and treatment methods are adopted.

4.32. — (b) Granular processes

4.32.1. Granular activated carbon (GAC) is used in fixed beds normally in enclosed columns. Most of the carbon is manufactured from bituminous coal although coconut shell charcoal is sometimes used for higher grades. Besides the adsorptive characteristics of an individual carbon, the average diameter and abrasion resistance of the particles are important properties for operating columns.

4.32.2. The average diameter and range of diameters affect the liquid flow through the packed bed — the flow increasing with increase in diameter. Larger diameters give lower pressure drop and consequent reduction in pumping costs in columns operated undere pressure, and these larger granule sizes ease backwashing. However an increase in granule size slows the rate of adsorption.

4.32.3. Abrasion resistance is important, affecting losses from mechanical action of backwashing, column charging and discharging, transportation, and re-activation. Abrasion resistance is normally a function of the type of raw material and the degree of activation, but for a given carbon, re-activation has been shown to reduce this resistance. In a granular process the fine dust formed by abrasion must be removed and discarded, posing an extra process cost and increasing carbon consumption.

4.32.4. Granular activated carbon can be operated under gravity flow but this use in the wastewater field has been confined to tertiary treatment. It is usually operated under pressures up to 3.5 bar and with hydraulic loadings of between 5 and 10 $m^3/m^2/h$. Downflow operation may be used with or without previous filtration of the wastewater but in both cases the bed accumulates organic solids and backwashing and air-scouring must be provided.

4.32.5. Studies show that carbon loading increases with the equilibrium concentration of the organic material in the wastewater. Therefore carbon just leaving the column should be in contact with the highest concentration of organics and giving the highest carbon loading. Two or more columns may be used in series for this counter-current operation with the last column containing fresh carbon. This system has the disadvantage that the pressure drop in each column is additive requiring extra pumping and thus extra energy. The pressure drop in columns operating in series may be overcome partially by up-flow pumping. Single columns are sometimes fed upwards through the bed at a rate expanding it (fluidising) to a pre-determined amount up to 50% and depending on the size of the carbon used but generally in the range of 15 to 24 $m^3/m^2/h$.

4.32.6. Alternatively parallel columns may be used, started in staggered sequence. Poorer quality effluent from more heavily loaded columns can be blended with higher quality effluents from columns with lighter loaded carbon achieving up to twice the loading on the carbon in a single contactor system.

4.32.7. 'Moving bed' or 'pulsed' operation gives the closest approach to a counter-current system. Slugs of fresh carbon are fed periodically to the top of an upward flow column with a similar amount of spent carbon being removed from the base. The flow rate is kept low enough to prevent fluidisation of the bed to minimise mixing of fresh and used carbon. The bed expands less than about 10% at these rates and the column tends to act as a filter. Since frequent backwashing mixes carbon unduly, this type of operation is best applied in tertiary treatment systems where deposition of solids and biological growth within the column are lower.

4.32.8. Experience with granular activated carbon systems is now extensive. Full scale plants have been constructed in both the United States and South Africa. Many systems include biological stages and are therefore dealt with in Paragraph 4.36. Physical-chemical treatment without a biological stage imposes heavy loads on the carbon. Such systems have been studied on pilot plants in the United States, Canada and the United Kingdom and full scale plants have been built in the United States.

4.32.9. A lengthy series of investigations have been carried out at Los Angeles County Sanitation Districts' Advanced Waste Research Facility in Pomona, California. The adsorption stage consists of a single 270 m^3/d downflow column containing 2,360 kg activated carbon. The feed to the column receives chemical clarification with alum at 25 mg/l as Al but no media filtration. Appendix A18/2 gives the performance of three adsorption cycles. The results indicate that the effluent produced could be considered to be within the United Kingdom 'Royal Commission' standard and also that the percentage removal is satisfactory.

4.32.10. The study at Blue Plains, Washington, was to aid the design of the full scale plant. The 243 m^3/d feed to the carbon columns had been clarified with lime and filtered. The carbon columns were two-stage series downflow with a total volume of 3.85 m^3. Appendix A18/3 indicates the capability of this type of plant to produce high quality effluents.

4.32.11. The first full-scale physical-chemical plant incorporating activated carbon treatment was commissioned in 1973 at Rosemount, Minnesota. It was designed for an ultimate average flow of 2270 m^3/d and contained chemically-aided settlement, dual media filtration, carbon adsorption, second stage filtration, ammonia exchange and chlorination. Apart from the chlorination system, the plant was divided into two separate streams. From June 1975 to May 1976, the average raw sewage flow to the plant was 871 m^3/d. Appendix A18/4 summarises the performance figures for this period. The high biochemical oxygen demand in the effluent from the carbon columns should be noted.

4.32.12. Another full scale physical-chemical plant has been installed at Rocky River, Ohio, designed to give activated carbon treatment to 37,850 m^3/d following alum coagulation and settlement. The carbon columns were designed for filtration and adsorption. Appendix A18/5 gives average performance figures for the 6 months ending March 1976. The plant produced a good effluent well within the United Kingdom 'Royal Commission' standard (4.32.18).

4.32.13. Information from Pomona and Rocky River in the United States highlights the generation of hydrogen sulphide within the carbon columns. Apparent biological growth within granular carbon systems was noted during pilot studies, and operational experience has confirmed this. This growth usually results in hydrogen sulphide in the effluent as micro-organisms within the column under anaerobic conditions tend to use sulphate as an oxygen source, reducing it to sulphide. Growth of these micro-organisms may lead to excessive head-loss building up after backwashing. Since micro-organisms are attached to carbon the backwashing only removes excessive growth and may indeed encourage a more vigorous population. Chlorinating and adding copper salts have not noticeably inhibited growth.

4.32.14. The organic loadings achieved on operational plants were soon shown to be significantly higher than laboratory tests had indicated. It was suggested that with appropriate design, the biological action could be exploited usefully by supplying an alternative source of oxygen to the sulphate in the effluent. Adding oxygen was unsuccessful, surprisingly, whereas adding nitrate as an indirect oxygen source overcame sulphide nuisance completely at Pomona. Appendix A18/6 details the steps taken to deal with this problem.

4.32.15. Although promoting biological growth by adding nitrate increases head loss, it increases the apparent treatment capacity. From a commonly accepted loading to exhaustion of 0.5 kg COD/kg carbon, the life of the activated carbon was extended: at regeneration it had apparently adsorbed 3.5 kg COD/kg carbon. The breakdown of adsorbed organics by microorganisms thus enhanced the life of the carbon.

4.32.16. The ability of activated carbon to remove metals has been investigated. Their removal by chemically-aided settlement is mostly marginal. However hexavalent chromium, is removed only in small quantities by chemically-aided settlement. Up to 99% was effectively removed by activated carbon. activated carbon.

4.32.17. As municipal wastewaters in Europe are generally stronger than those in North America the United Kingdom has tried for several years to quantify the performance capabilities of activated carbon. Bench scale (10.4 l/d) work at the Stevenage Laboratory indicated some of the limitations of physical-chemical treatment for higher strength wastewaters. Whilst Stevenage wastewater was strong, even for the United Kingdom, the results presented in Appendix A18/7 indicate the difficulty of achieving a high quality effluent. Therefore the performance of activated carbon plants in the United States must be interpreted with caution in the European context.

4.32.18. A small scale (10 m^3/d) activated carbon system at Coleshill was used to analyse the effluent produced from physical-chemical treatment for comparison with the effluent from a small scale activated sludge plant providing full treatment. Appendix A18/8 gives the biochemical oxygen demand (BOD_5), the chemical oxygen demand (COD) and the total organic carbon (TOC) figures for the two effluents. Although concentrations of organic substances indicated by COD and TOC were much lower in the effluent from the physical-chemical plant, the BOD_5 was higher, but not unexpectedly since physical-chemical unit processes are not particularly efficient at removing highly water-soluble molecules which may exert a significant biochemical oxygen demand.

4.32.19. Appendix A19 gives full details of the analyses. The main conclusions were that carbon treated effluents were less complicated, except for a diversity of sulphides produced under anaerobic conditions in the columns. Many compounds occurred in both effluents. Whilst many other compounds in biologically treated effluents did not occur in physical-chemical treatment effluents, relatively few not in biologically treated effluents were found in the physical-chemical treatment effluents.

4.32.20. Results from the carbon adsorption stage in the later experiments at Coleshill quoted in Appendix A18/9 showed much the same picture as from all higher strength wastewaters including the results from Rosemount, Minnesota in that it failed to produce a United Kingdom 'Royal Commission' effluent (see Appendix A18/4) But it should be remembered that the United Kingdom 'Royal Commission' standard is somewhat arbitrary.

4.32.21. That compounds appearing to pass through activated sludge treatment may be removed by activated carbon opens up the possibility of producing effluents of very high standards with a combination of activated sludge, and activated carbon processes and this is worthy of serious consideration in the design of future treatment plants for wastewaters containing a high proportion of complex industrial wastes.

4.33. — (c) Powder processes

4.33.1. Powdered activated carbon (PAC) was used initially in potable water treatment to remove substances causing occasional nuisance. Added directly to the water, it has a rapid action and can be removed by sedimentation/filtration. Whilst powdered activated carbon is cheaper than granular activated carbon it has to await a proven method of regeneration before it can be considered an economic competitor. Development of regeneration techniques on pilot scale for powdered carbon has opened up the possibility of usuing it for wastewater treatment in the future.

4.33.2. The basic process in wastewater treatment consists of adding, mixing, contact and separating powdered carbon. It can be added as a powder or slurry to suit the organic strength of the wastewater. After rapid mixing, a contact time of fifteen to forty five minutes suspension is allowed in an upward flow clarifier from which the effluent will contain a substantial amount of fine carbon and will need filtering. The carbon settled in the clarifier is withdrawn as a slurry, gravity thickened and vacuum filtered prior to regeneration.

4.33.3. Organic polymers are often added to the clarifier to improve the settling properties of the carbon. Work has been carried out with pilot-scale fluidised beds of flocculated carbon able to accept high overflow rates of about 5 m/h.

4.33.4. Much experimental work has been carried out over a period of years at the Salt Lake City Plant of the Eimco Corporation. The system employed either one or two stage contact clarifier units for carbon treatment following chemically-aided settlement. Detailed discussion of results is presented by Burn et al in the Environmental Protection Agency Technology series publications. Appendices A20/1 to A20/6 show summary results of six different sets of operating conditions.

4.33.5. The main conclusions of this work were submitted as:

a. When employing alum of ferric chloride pretreatment, two stage counter-current powdered carbon contacting (at 100 mg/l carbon) and typical diurnal flow conditions, the 'PAC-PCT' process produced a consistently high quality effluent of less than 5 mg/l COD, 5 mg/l SS and 0.3 mg/l phosphorus.

b. When properly operated, the carbon stages performed satisfactorily during diurnal flow conditions.

c. Soluble organics (COD) were removed by chemical coagulation, anaerobic biological activity and adsorption on activated carbon in the 'PAC-PCT' process.

d. No significant treatment or cost benefits stemmed from counter-current staging of powdered carbon contacting.

4.33.6. A powdered activated carbon system has been investigated by Environment Canada as part of a physical-chemical treatment process. This was particularly relevant to treatment processes for small communities and was aimed not only at ultimate regeneration of the carbon but also at the evaluation of low grade activated carbons for use on a once-through basis. The use of package plants for construction sites etc. was investigated. When alum was added at 200 mg/l, powdered activated carbon at 100 mg/l and organic polymer, the effluent was well within United Kingdom 'Royal Commission' standard. However when sludge from the final treatment clarifier was recycled back to the carbon contact tank the quality of the effluent deteriorated even though it was still within the United Kingdom 'Royal Commission' standard. Appendix A21 gives the results.

4.34. — (d) Regeneration

4.34.1. Regeneration restores activated carbon which has become saturated with adsorbed compounds to as near its original state as practicable and preferably should be carried out with minimum loss of carbon. Regeneration is an essential part of any economically competitive physical-chemical treatment plant. For wastewater treatment plants with capacity greater than 3750 m³/d the cost of regeneration on the site has been shown to be only 20-30% of the cost of fresh carbon.

4.34.2. Chemical regeneration has been studied in the United States and France and involves washing the carbon with caustic soda followed in France by hot solvent. This process may be useful to recover the adsorbed material, but may not have a role in municipal wastewater treatment where this recovery is not necessary and a wide variety of compounds are adsorbed.

4.34.3. Biological regeneration has been used for textile dye waste where carbon passes through an aerobic biological culture and the adsorbate is oxidised microbially. Such processes may only apply when complete regeneration is not required.

4.34.4. Thermal regeneration is the only proven method for reactivating carbon after treating municipal wastewaters when a wide variety of compounds may have been adsorbed. Thermal regeneration involves three basis steps: first the carbon is dried with a gas temperature between 200°C and 300°C and the free water is evaporated into the gas stream. The second stage breaks down the adsorbed material driving off volatiles by destructive distillation with a gas temperature between 400°C and 800°C. In the third stage, the organic char and some of the carbon structure are activated by oxidation with carbon dioxide from the combustion gases and steam with temperatures from 800°C to 1000°C. The oxygen content of the activated gases must be low to prevent excessive burn off of carbon. On leaving the furnace the carbon is often quenched in water to 40°C although some systems merely cool the carbon in air.

4.34.5. Regeneration has presently been limited to granular carbon. Two common methods are available. The multi-hearth regeneration furnace illustrated in Appendix A22 contains between five and seven hearths. The spent carbon is fed in at the top and passed down by centrally rotated rabble arms. The carbon is moved alternately towards the centre in one hearth and away from the centre in the next hearth with drop holes to reach the following hearth. Burners are usually installed on the lower three to five hearths. Rotary kilns as illustrated in Appendix A23 have been used extensively to regenerate spent bone char and carbon in the sugar refining industry and are now tending to replace multi-hearth furnace for carbon regeneration.

4.34.6. Powdered activated carbon cannot be regenerated by either multi-hearth or rotary kiln because rapid oxidation leads to excessive loss. Also, the cost of the use, regeneration, make up cycle is comparatively high for both methods notwithstanding powdered carbon being cheaper than granular carbon. The Westvaco Corporation Covington, Virginia has developed a transport reactor for recovering carbon from sugar refining operations. It could be regarded as the only full scale application of powdered carbon regeneration in which particles of wet spent carbon are entrained in an upward moving stream of hot combustion gases. The mechanism of reactivation is similar to all thermal systems but occurs in one second or less whereas carbon stays in a multiple hearth furnace for about 30 minutes.

4.34.7. The 'Fluidised bed' furnace illustrated in Appendix A24 has received a great deal of attention at pilot scale. Powdered carbon is pumped into a sand bed which is fluidised by hot combustion gases and passes upward through a distribution plate. The operating temperature is from 700°C to 900°C and a short retention time prevents excessive carbon being burnt-off.

4.34.8. Other systems proposed for powdered carbon regeneration include 'atomised suspension' which is an indirect method of heating and 'wet air oxidation' in which the carbon and primary chemical sludge are heated to between 200°C and 250°C. This latter technique of containing the carbon within the sludge has been put forward for use with an electric furnace developed by Shirco Inc. of Dallas, Texas, in which regeneration heat is supplied by infra-red radiation.

4.34.9. Before starting a regeneration cycle laboratory tests are usually made to obtain approximate temperatures for complete regeneration. These could be in a muffle furnace modified for the injection of steam and carbon dioxide. Regeneration can be monitored by the change in weight of a carbon sample and subjecting the regenerated carbon to standard tests for activity.

4.34.10. Not all the original carbon can be recovered in its virgin condition and the aims of achieving high yields of carbon and high activity must be balanced. In practice it is usual to aim for the same original activity and accept a lower yield. However the relative economics of the process have not been studied in detail and there may be a minimum cost procedure of deliberately under-regenerating to reduce carbon loss albeit with frequent regeneration. Losses of carbon during the whole cycle have been reported as between 1% and 10% with an average of 4% but not all this is attributable to pure regeneration as attrition during handling contributes. Activated carbon is damaged easily by mechanical handling. The dust burns off rapidly in the furnace or is lost in backwash water from the adsorption column. A loss of 5% carbon in each regeneration cycle is an operational feature of any activated carbon system.

4.34.11. Most regeneration work in wastewater has been carried out in the United States where about twenty plants are either installed or being designed. The first was probably that of the South Tahoe Public Utilities District, where regeneration has been practised for 10 years. Temperatures up to 940°C have been used, the average being 910°C (Appendix A25/1). Ash did not build up significatnly after four regeneration cycles. As the carbon was used in a tertiary physical-chemical process on effluent which had already undergone biological treatment the concentrations of pollutants at the carbon adsorption stage were therefore low (BOD_5 3 mg/l, COD 25 mg/l, SS 0 mg/l). No physical blockage of the carbon pores by solids would in be expected in these conditions and there would be little ash.

4.34.12. Regeneration was recently examined at Los Angeles County Sanitation District's Research Facility at Pomona, California. Activated carbon was used as the final stage of treatment in a physical-chemical treatment system without prior biological treatment and with no filtration after the primary chemically-aided settlement stage. Therefore the concentration of the pollutants in the carbon column feed was much higher than at South Lake Tahoe being BOD_5 36 mg/l, COD 96 mg/l, SS 40 mg/l, although still lower than that expected in Europe. The final effluent never deteriorated to the original exhaustion criterion of COD 40 mg/l and the carbon was regenerated on a time basis — after eighteen months for the first cycle and every three to five months thereafter. The three regeneration cycles were carried out (Appendix A25/2) at maximum temperature declining from 975°C to 946°C.

4.34.13. Interpreting the results leads to the conclusion that either the adsorbate was removed incompletely from the micropores or some of the micropores were completely burnt out. The latter may explain in part the slightly higher dissolved COD removal capacity of the regenerated carbon even allowing for adding nitrate (4.32.15). After the first regeneration cycle the ash content increased from 6.4% to 10.7% but fell to a final figure of 9.0% after the third regeneration. The ash content within the carbon is important as it occupies some of the pores making them unavailable for adsorption. More of the carbon structure must be activated to maintain the same activity leading eventually to greater carbon losses. Alternatively, reduced adsorption must be accepted. Whilst no direct evidence is available ash build up will probably be of greater concern when carbon used for treatment of higher strength wastes is regenerated in the Coleshill furnace.

4.34.14. A regeneration furnace was commissioned at the Stander Water Reclamation Plant, Pretoria, South Africa, in 1976. After regenerating at 930°C, the temperature was reduced to 830°C to conserve fuel consumption and minimise thermal wear on the furnace. Contrary to expectations, the lower temperatures appeared to yield a more completely regenerated carbon.

4.34.15. Recently highlighted damage to the interior of multiple hearth furnaces by gases from carbon regeneration may cause concern. Whilst this is particularly relevant to plants treating industrial wastes, the possibility that inorganic impurities adsorbed, mainly chlorides and sulphates, may be liberated as acidic gases must be borne in mind in municipal wastewater treatment, and corrosion of flights and the central shaft may be expected. Slag building up in the furnace will also lead to shutting down for repairs. The refractory lining of a multi-hearth furnace can be damaged by temperature fluctuations which can result from interrupting the carbon feed. Some form of gas cleaning system is needed prior to discharge to the atmosphere, including a bag filter or scrubber to remove particles. An afterburner is often installed to promote complete combustion of gases. Whilst the afterburner was seldom used at South Tahoe, experience at Pomona indicates that the flue gases were more noxious when heavy loads were imposed on the carbon, necessitating afterburners. After-burning may need one third as much fuel as that required for regeneration.

4.35. Ammonia Stripping — **(a) General**

4.35.1. The ammonia stripping process comprises raising the pH of the feed wastewater, and forming and reforming wastewater droplets after pumping the feed to the top of the stripping tower and promoting intimate air/droplet contact by circulating large volumes of air through the tower. The ammonia is discharged in gaseous form. Thus stripping may conveniently follow lime-aided settlement, which produces high-pH effluents.

4.35.2. The urea (derived from urine) present in 'fresh' wastewater is hydrolised to ammonia by the naturally-occurring enzyme urease, complete hydrolysis taking 12 hours or more.

4.35.3. The form in which the ammonia is present depends on the wastewater pH. At pH7, only ammonium ions in true solution are present whereas at pH12 there is only dissolved ammonia gas and it is the gas that can be stripped. Very large amounts of air are needed for stripping.

4.35.4. Two types of stripping tower have been used: counter-current in which the air supply is introduced at the base of the tower and flows to the top; and crossflow in which air is introduced progressively through the tower sides throughout their height.

4.35.5. Wastewater generally reaches atmospheric temperature in the top few centimetres of a stripping tower. Process efficiency falls off at low temperatures; 90% removal can normally be achieved at 20°C, but only 75% at 10°C; icing occurs at a wet-bulb atmospheric temperature below zero and the process has to be shut down.

4.35.6. The wastewater must fall through the tower in droplets, not sheets. This will normally be ensured if loading rates do not exceed 141 m^3/m^2 of plan area of tower packing. Even distribution of flow is very important.

4.35.7. The calcium hydroxide in limed wastewater and the carbon dioxide in the circulating air cause calcium carbonate scale to be deposited on the tower packing which progressively reduces the cross-sectional area available for liquid/air contact. Soft scale may be removed by jetting provided suitable arrangements are made during design. Counter-current towers may be less prone to scaling than crossflow types.

4.35.8. At South Lake Tahoe wastewater treatment works, California, no scaling was observed on the pilot counter-current tower but severe scaling occurred on the operational crossflow tower. Improvised jetting easily cleared scale from those portions of packing accessible for cleaning. At Blue Plains, Washington DC, scale hardness seemed to vary with feed pH — the higher the pH, the harder the scale.

4.35.9. At Windhoek, South Africa, a soft and easily-removable scale has been reported, the 57,000 m^3/day tower built recently at Orange County, California, has packing removable for cleaning.

4.35.10. Ammonia gas concentrations in discharges from stripping-towers have often been about 6 mg/m^3 when domestic wastewaters were being treated with an air flow 3.1 m^3/l and feed ammonia 23 mg/l. The smell-threshold of ammonia is 35 mg/l. Ammonia gas is stable and does not form nitrogen oxides in the atmosphere. There are no known public health implications.

4.35.11. Typical design criteria are:
Hydraulic loading 70 to 2114 $m^3/m^2/d$
Air-to-water ratio 300 to 500 ft^3/minute per gallon/minute
Air-pressure drop 13 to 32 mm
Packing depth minimum 7.6 m
Packing spacing (horizontal and vertical) 51 mm to 102 mm.

4.35.12. A modified technique aimed at reducing temperature and scaling difficulties involves holding feed in high-pH surface ponds before crossflow stripping by means of air-sprays housed in a tower, followed by breakpoint chlorination. This is being adopted at South Lake, Tahoe.

4.35.13. Appendix A26 shows another possible technique. The stripping-gas, initially air, is maintained in a closed cycle from which ammonia may be recovered. The ambient carbon dioxide which is the root cause of scaling is eliminated during the first few passes.

4.36. — (b) Orange County plant

4.36.1. The Orange County works has a dry-weather flow of 57,000 m³/d and was built in conjunction with an 11,000 m³/d seawater desalting plant. Biological filter effluent is treated with lime to pH 11, settled and the liquor passed through two ammonia-stripping towers. Air is passed through heat-exchangers located in the base of the towers, which cool the desalting process water and warm the air, and then to the ammonia stripping section. The towers are designed to operate at 31-33°C, to avoid problems with freezing.

4.37. — (c) United Kingdom experiment

4.37.1. Experiments on the small stripping tower at the Stevenage pilot plant have generally confirmed experience in the United States, but even larger volumes of air were needed to achieve useful reductions in ammonia on this strong United Kingdom wastewater. About 5700 volumes of air were required per unit volume of feed to remove 80% of the 40 mg/l — 60 mg/l of ammonia present in the lime-settled wastewater. The air supply had to be increased to 8800 volumes/volume of feed to remove anothr 5% of the ammonia.

4.37.2. It was observed that up to 30% of the total nitrogen might remain as unhydrolysed urea in stripping-tower effluent. This could not be removed by air stripping. It was not likely to be adsorbed by any subsequent activated-carbon process; if it were it might be hydrolysed during the process and re-emerge in the effluent as ammonia.

4.37.3. Hydrolysis of urea is inhibited at pH 10.5 and above. Thus when ammonia is to be removed in the United Kingdom by air stripping the raw wastewater might first be treated in a high-rate activated-sludge plant in which the urea would be rapidly hydrolysed and the effluent then limed prior to stripping.

4.38. — (d) Use of selective ion exchange

4.38.1. Zeolites with a selective action for ammonia relative to calcium, magnesium and sodium have been used to remove nitrogen in the United States. Clinoptilolite, which occurs naturally in the west of the country, has been found especially suitable, when crushed and sieved through a 20 × 50 mm mesh.

4.38.2. Pilot studies on a flow of 450 m³/day showed that 96% of an ammonia concentration of 20 mg/l in the feed could be removed at hydraulic rates of 7-15 bed-volumes/hours within a pH range of 4 to 8. After 150-200 bed-volumes of wastewater had passed the bed, ammonia began to leak through and the clinoptilolite needed regenerating with a salt solution. The volume of regenerant needed was 2.5%-5% of the throughflow and handling this ammonia-laden spent liquor was found to be the key to the viability of the process. Lime slurry was used initially to convert the ammonia stripped from the bed into gaseous ammonia; later salt was added to speed-up the action. The regenerant was passed through a small stripping tower which could be heated economically. But precipitation of magnesium hydroxide and calcium carbonate caused scaling and the intense backwashing required to clear it wasted up to 0.25% of the clinoptilolite in each cycle.

4.38.3. Electrolytically-generated chlorine was used experimentally to convert ammonia in the regenerant solution to nitrogen gas at neutral pH thus avoiding the precipitation problems occurring with lime. About 50 Wh of power were needed to deal with 1g of ammonia nitrogen (NH_3-N); that is, about 2.2 kWh/m^3 of wastewater containing 25 mg/l MH_3-N.

4.38.4. Following this pilot-scale work, clinoptilolite beds with electrolytic treatment of regenerant were adopted for a 100,000 m^3/d wastewater treatment works at Upper Occuquan, Virginia, with softening of the regenerant by soda ash to avoid cathodic scaling of the electrolysis cells. Details are:

Exchange beds
8 No. 20x50 mesh clinoptilolite beds 3m diameter x 15m long, bed depth 1.2m. Average cycle loading 9 bed-volumes/h, maximum 14; average hyrdraulic loading 42 $m^3/m^2/h$, maximum 66. Service cycle length, 200 bed-volumes. Backwash with carbon-column effluent at a rate of 77$m^3/m^2/h$.

Exchange bed regeneration
Cycle length 3h at 10 bed-volumes/h.

Electrolytic regenerant recovery
Power requirement 40 Wh/g NH_3-N destroyed. 480 service cells, each with destruction rate of 0.073 kg NH_3-N/h, total cells provided, 720. Salt requirement 6300 kg/d.

4.39. — (e) Breakpoint chlorination

4.39.1. When chlorine is added to wastewater, the ammonia content reacts with the hypochlorous acid formed to produce chloramines. Adding chlorine to the breakpoint at which the chlorine residual reaches a minimum converts the chloramines to nitrogen gas and removes the ammonia. The reaction takes only about a minute in the range of pH from 7 to 8.

4.39.2. In theory a ratio by weight of 7.6 parts of chlorine are needed for each part of ammonia nitrogen present in the wastewater but the actual ratio was found to vary with the degree of pre-treatment given. These ratios were 10:1 for raw wastewater, 9:1 for conventional secondary effluent and 8:1 for limed and filtered secondary effluent. Little nitrous oxide was formed. Ambient temperatures between 5°C and 40°C did not affect either the effluent or the chlorine dose.

4.39.3. Adding chlorine produces an equivalent weight of hydrochloric acid which depresses the pH unless the wastewater has high natural alkalinity or a base such as sodium hydroxide is added. Nitrogen trichloride (NCl_3), which has an intolerable smell, is formed at lowered pH. Mixing must be extremely vigorous when a base is added as even small localised pockets of NCl_3 would be objectionable. Sodium hypochlorite could be used instead of chlorine to obviate the NCl_3 difficulty:

4.39.4. An Environmental Protection Agency study showed that 14.3 mg/l of alkalinity as CA CO_3 were needed to neutralize the acid produced by the oxidation of 1 mg/l ammonia nitrogen to nitrogen gas. When lime or sodium hydroxide was added the total dissolved solids — already bound to rise because of chlorination — would increase further. The requirements for chlorine and alkalinity and the quality of dissolved-solids produced would all fall if chlorination formed only monochloramines which could be removed on activated carbon. Pilot studies revealed that only about 50% of the ammonia would be removed but that contact with carbon for ten minutes would deal with the monochloramines. Monitoring the incoming ammonia in conjunction with automatically controlled dosing of chlorine is essential for all systems.

4.39.5. A number of plants in the United States use breakpoint chlorination either to remove ammonia remaining after air-stripping (South Lake Tahoe, Orange County) or as the primary process to remove nitrogen (Montgomery County). With a cost of chlorine of 0.15 cents/kg, a Cl:N ratio of 8:1 and an ammonia concentration in the feed of 25 mg/l, the cost of chlorine alone would be 2.6 cents/m³. The cost of pH control would be in addition to that.

4.40. — (f) Biological denitrification

4.40.1. Biological denitrification appears to be the most promising way of removing nitrogen. It is not a physical-chemical process but has been used in conjunction with chemically aided settlement.

4.40.2. Chemically-aided settlement was practised at Contra Costa, California, with 400 mg/l of lime as $Ca(OH)_2$ and 14 mg/l of ferric chloride, to pH 10.5-11. The tank effluent was passed to a completely-mixed nitrifying activated-sludge reactor. Provided that the pH of the feed did not exceed 11, the carbon dioxide produced by oxidation of dissolved organics and the acidic conditions produced during nitrification maintained to pH at about 8.0-8.3; optimal for nitrification. Following this aerobic treatment, the liquor was fed to a completely-mixed anoxic activated-sludge reactor to which methanol was added as a carbon source to speed-up the process and in which the sludge was kept in suspension by stirring. Facultative micro-organisms in the sludge utilized the nitrate produced in the previous stage as an oxygen source and nitrogen was released to the atmosphere. The following figures were typical:

Parameter (mg/l)	Raw wastewater	Limed effluent	AS effluent	Denitrified effluent
SS	214	26	5	4
BOD_5	203	57	4	3
TOC	122	42	9	9
Amm-N	—	24	0.5	0.3
NO_3-N	—	—	27	0.5

4.40.3. A small nitrification/denitrification sidestream was provided on the Stevenage pilot plant. The flowrate was steady at 114 litres/h and retention times in the nitrifying activated-sludge reactor and in the anoxic reactor were 4 hours and 1.1 hours respectively. Sludge ages were about 17 days in the nitrifying system and 16 days in the anoxic denitrifying system. The mixed liquor suspended solids in the two systems were about 3800 and about 5300 mg/l respectively. Limed effluents with a pH up to 11.6 could be handled. For full denitrification, the minimum carbon-nitrogen ratio was about 0.94. Methanol was used as the carbon source. Over 90% of the nitrogen was removed even from the strong Stevenage wastewater. Typical figures were:

Parameter (mg/l, except for pH)	Raw wastewater	Limed effluent	AS effluent	Denitrified effluent
pH	7.2.	11.6	8.0	8.1
BOD_5	500	177	4	9
COD	1020	266	42	60
TOC	340	92	17	22
Kieldahl-N	70	49	2	4
Amm-N	35	20	< 0.4	< 0.4
NO_3-N	< 0.4	1	36	< 0.4
% removal of N	–	30	45	95

4.41. Combined Physical-Chemical and Biological Treatment — (a) Background based on original United Kingdom views at the start of the study (1972)

4.41.1. As a preable to describing the experimental work, we think it important to set the scene in the United Kingdom as at the start of our work.

4.41.2. At the risk of over-simplifying the presentation, we then thought we would only need physical-chemical processes to assist the mechanical/physical/biological processes to remove those substances not thereby removed more effectively and which we need removed. These substances comprised non-bio-degradable matter which were not affected by the traditional treatment stages, the more resistant bio-degradable materials which had also escaped significant treatment, and the very fine solids in suspension and dispersion which had defeated the traditional treatment in the mode in which it was used. These included soluble organic and residual colloidal material and biologically intransigent organic substances.

4.41.3. With careful plant design, construction, operation and management we could provide traditional biological treatment stages in most cases to take the main load and particularly when those had been further developed, optimised, and incorporated automated control. They were expected to suffice in most situations envisaged within at least the next decade in the United Kingdom especially when the discharge requirements for effluents had been matched realistically to the local needs of the receiving waters. Whilst it was thought feasible to develop special bacteria to treat wastewater that could not be treated by the conventional biological methods using naturally occurring organisms, these new organisms could bring their own problems and the new hazards might be worse than the old. We deferred ventures into genetic engineering until all other available options for treatment have proved to be unsatisfactory: until there is no acceptable alternative.

4.41.4. In the remaining few cases where the developed traditional treatment was not enough and we needed extra removal capability, this had to be provided irrespective of constraints such as total cost. It had to be designed specifically to meet the need for it and function expeditiously, effectively and reliably, preferably with an accurately predictable performance.

4.41.5. Domestic wastewaters may have needed additional treatment such as chemically aided settlement to reduce phosphorus markedly but ammonia and nitrates were best reduced or removed by improved traditional processes. When industrial wastewater was included we may often have needed chemical aids to precipitate particular substances and adsorptive activated carbon to remove specific pollutants — and probably protected by preceding multi-media filters. This carbon stage removed large molecules (some non-bio-degradable) well, but removed smaller soluble molecules such as aliphatic acids less well.

4.41.6. The sophisticated, expensive and energy-intensive processes such as ultrafiltration, reverse osmosis, electrodialysis, ion exchange distillation and freezing would probably only be used when we needed very high quality water. Disinfection of effluents was unlikely in any situation other than direct re-use if we ever contemplated that.

4.41.7. Conversely in the comparatively less common situation when we processed wastewater in a physical/chemical treatment plant we needed a complementing biological stage to remove the bio-degradable organic content more effectively at lower cost. This had to be a suitable process to do the required work best and be placed where it would have most effect in the combined treatment chain.

4.41.8. Introducing the biological stages would have increased the capital cost of the treatment chain and may have increased the energy required but some of this would be offset by reduced capital and running costs of the comparatively very expensive activated carbon plant due to the smaller capacity then needed. Adding activated sludge might have impaired the thickening and dewatering characteristics of the sludge from the chemical treatment stage and might also have given unpleasant odours. There might have been a case for keeping the activated sludge separate from the other sludges.

4.41.9. Whilst we have directed the comments already made towards new treatment works for wastewaters containing trade wastes and non-bio-degradable matter, we could have relieved existing conventional treatment works that were much overloaded by coagulation and flocculation and/or activated carbon stages. Feasibility would have depended on the quality of the incoming wastewater and the final effluent standard, the physical layout of the plant, and the space available for future extensions and of course costs. Thus in future in the United Kingdom it appears that whatever type of treatment plant is considered initially, some combination of mechanical, chemical, biological, and physical stages would be needed ultimately — and possibly in that order — if optimized treatment is to be provided at lowest cost.

4.41.10. We now review in detail the related work done in the field in the United Kingdom, in Canada, in Norway, in the United States and in France.

4.42. — (b) United Kingdom

4.42.1. This work was done with the pilot plant at Davyhulme and comprised first the lime aided settlement of an effluent from an activated sludge stage.

The train of processes was:

Process	Retention (h)	Surface overflow rate (m³/m²/d)
Primary settlement	1.8	38
Activated sludge	1.1*	—
Intermediate settlement	1.8*	19
Liming to various pH values	—	—
Final settlement	1.8	38

* allowing for 100% sludge return

Flowrate was steady at 147 m³/d. The pH values were successively 10.5, 11, 11.5 and 11.75.
Appendix A27 shows the results at pH 11.5 and 11.75.

4.42.2. Results were generally disappointing although reasonable removal of additional BOD_5 from 14 mg/l to 9 was obtained at pH 11.5 and from 19 mg/l to 11 at pH 11.75. Nearly all limed effluents at all pH values contained more suspended solids than those from intermediate settlement. As they looked quite clear the samples were analysed whilst fresh and after standing which induced precipitation and reduced soluble magnesium.

4.42.3. We then investigated the treatment of limed wastewater with activated sludge. The train of processes was:

Process	Retention (h)	Surface overflow rate (m³/m²d)
Liming to various pH values	—	—
Primary settlement	1.5	38
Activated sludge	1.2*	—
Final settlement	1.5*	19

*% allowing for 100% return sludge

Flowrate was steady at 147 m³/d and pH values were successively 10, 10.5, 11 and 11.5 Appendix A28 shows results.

4.42.4. Effluents were generally of high quality, particularly when liming was to pH 10.5 and above. They were thought suitable for further treatment for producing effluents for the industrial re-use which was always an ultimate aim of the Davyhulme work. They also varied less than those from control. The advantages of this smoothing effect — illustrated in Appendix A6 — were demonstrated when, on more than one occasion, new high-strength industrial effluents in the wastewater were treated without either difficulty or the need to adjust operating conditions on the pilot-plant.

4.42.5. Liming reduced the organic strength and suspended solids content of the tank effluent passing forward for aeration and therefore reduced the load of organic and sludge-forming matter on the activated sludge stage. These factors and the additional calcium compounds in the tank effluent, resulted in increased mineral content in the activated sludge. Mineral content increased successively as pH was raised in accordance with the experimental programme. When the wastewater was being limed to pH 11.5, mixed liquor suspended solids in the activated sludge reactor averaged 12170 mg/l, of which only 5160 were volatile solids. Thus the activated sludge contained 58% inorganics. During control experiments without liming and at the lower pH values the suspended solids in the mixed liquor were normally held around 4000-5000 mg/l.

4.42.6. Although facilities employing acid were available on the pilot plant for reducing pH they were not needed during this experiment. Effluents from primary-tanks had pH values from 0.4 to 0.9 below those of limed wastewaters and the pH values of mixed liquors and final effluents were commonly about 9 and 8 respectively. We calculated that 217 parts of CO_2 were produced for every 100 parts of BOD_5 fed to the plant. In round figures, when plant throughput was 150 m^3/d and 200 mg/l of BOD_5 was removed, 30 kg BOD_5/d would be disposed of corresponding to 65 kg CO_2/d — equivalent to 84 kg CaO/d. As the maximum daily quantity of lime added was 60 kg CaO, it would seem in theory that enough CO_2 was produced to convert the lime to carbonate.

4.42.7. Although lime aided settlement removed about 75-85% phosphorus, enough remained as nutrient in the activated sludge process. The figures in Appendix A5 show that when the phosphorus/feed-BOD_5 ratio fell to 0.3/100 at pH 11.5 the effluents were still good though marginally less so than at pH 11.

4.42.8. Frequently and unpredictably the Davyhulme wastewater is coloured by solutions resistant to biological oxidation and emanating from manufacturing dyestuffs and dyeing textiles. Reds, yellows and purples predominate. Colours were measures systematically during this and the preceding phase of the experiments. Appendix A29 shows the results recorded as high adsorption values in the red, yellow and blue range of the visible spectrum through a 1-in cell in a Lovibond Tintometer. Settling without chemical aid had no noticeable effect. Activated-sludge treatment reduced colour to some extent especially the yellows; liming the activated-sludge effluent reduced them considerably. Colour was reduced substantially in tank effluents from limed raw wastewater but the subsequent activated-sludge treatment removed little more.

4.42.9. The most probable numbers (MPN) of total coliform bacteria and of Escherichia coli regarded as of faecal origin were determined in this and in the preceeding phase of the experiment. Total coliforms in raw wastewater varied from 35 to 1254 x 10^3 per ml, averaging 400 x 10^3: E. coli varied Early results showed that *Cl* welchii, initially present in numbers lower by an was within the normal range. After conventional primary settlement coliforms and E. coli averaged 300 and 200 x 10^3 per ml respectively but dosing with lime to aid primary settlement reduced E. coli by almost three orders of magnitude to 0.3 x 10^3. Treating unlimed tank effluent with activated-sludge gave coliform and E. coli counts of about 50 and 25 x 10^3 per ml respectively but when lime-aided settlement followed the activated-sludge treatment both counts were similar to those quoted above for lime-aided primary settlement.

4.42.10. Thus liming exerted a significant sterilising effect whether carried out on raw wastewater or on activated-sludge effluent and clearly was a useful step towards producing a final effluent for industrial re-use. More specific quantitative information of public health interest is being obtained by determining the MPN of Clostridium welchii and numbers of salmonella. Early results showed that *Cl* welchii, initially present in numbers lower by an order of magnitude than E. coli, were not reduced so consistently by lime-aided settlement and were not affected significantly by treating with activated-sludge. Salmonella showed similar tendencies though present initially in lower numbers than Cl welchii.

4.42.11. Appendix A28 shows that lime-aiding primary settlement reduced the surplus activated-sludge substantially, an operational advantage.

4.42.12. Appendix A15 shows sludge dewaterability.

4.42.13. We have started experiments with adsorption on activated carbon. Preliminary runs on the sand filter/granular activated carbon units using feed from the activated-sludge treatment of limed wastewater produced effluents with the following characteristics:

Suspended solids	6 mg/l
BOD_5	5-8 mg/l
COD	53-80 mg/l

Process details are given in para 4.42.1. Little further colour was removed.

4.43. — (c) Work in Canada

4.43.1. A new works at Guelph designed to treat a dry-weather flow of 18000 m^3/d was divided into two identical parallel plants to assess the effects of alum dosing on an otherwise normal diffused-air activated-sludge plant. This was planned in connection with phosphorus removal under the Great Lakes Agreement.

4.43.2. One plant was used as the control. On the other plant 100 mg/l alum and 4 mg/l activated silica, dosed according to flowrate, were added 6 metres from the end of the last aeration channel with air supply adjusted to induce a rolling motion promoting flocculation. The dose-rates had been selected during earlier experimental work for optimum phosphorus removal.

4.43.3. Detention periods and overflow rates for each plant during five phases of experimentation were:

Phase	Flowrate (m^3/d)	Primary		Aeration		Final settlement			
		Det. time (h)	SOR ($m^3/m^2/d$)	Det. time (h)		Det. time (h)		SOR ($m^3/m^2/d$)	
				NR	R	NR	R	NR	R
1	6636	3.04	24.0	6.75	4.56	4.40	2.99	19.9	29.4
2	8772	2.31	31.7	5.10	3.74	3.35	2.46	26.3	33.59
3	10690	1.91	38.2	4.23	3.25	2.78	2.13	31.8	41.4
4	11544	1.75	41.7	3.88	3.04	2.55	2.00	34.7	44.2
5	11499	1.76	41.5	3.89	3.05	2.56	2.00	34.5	44.1

NR = no sludge recirculation
R = sludge recirculation
SOR = Surface overflow rate

The flowrates quoted are average dry-weather flows; actual flows were subject to diurnal and other variations and were identical on each plant. Sludge could be returned at varying rates and is not allowed for in the figures given above. Appendix A30 shows results.

4.43.4. During phase 1, when the plants were under-loaded, alum effluents were better than those from control with suspended solids 20 and 39 mg/l chemical oxygen demand 93 and 125 mg/l respectively. During phase 2, when both plants were close to design flow this did not occur. Alum then had little effect on either suspended solids or chemical oxygen demand and the results in phase 3, when there was 15% theoretical overload, were much the same. Establishing phase 4, originally intended to give 50% overload, was difficult. Billows of floc appears over most of the final settlement tanks and began to flow over final tank weirs. Although flowrates were reduced and return sludge was increased from 20% to 35%

the trouble persisted and the sludge settling velocity in the final tanks was then less than tank overflow rate. Flows had again to be reduced slightly to an average of 11,500 m^3/d in phase 5, a 25% overload. The effluent quality deteriorated during this final phase, suspended solids and chemical oxygen demand being 39 and 121 mg/l for alum and 26 and 116 mg/l for control respectively.

4.43.5. Plant operation, oxygen utilisation and sludge production and characteristics were investigated thoroughly with the following general conclusions:

a. Adding alum to the activated-sludge tank was confirmed as an effective means of reducing total phosphorus to 1 mg/l or less.

b. Its effect on reducing suspended solids and organics depended on hydraulic loading; below design load it increased removal, at design load it had little effect, and above design load it decreased removal markedly.

c. Alum mixed liquors were lighter, settled more slowly and were more easily broken-up than normal mixed liquors. Once disturbed they tended to be carried over final tank weirs and this was the principal cause for poor alum effluents during high loading conditions.

d. Accumulating alum precipitates in the mixed liquors, a function of dose and sludge age, meant maintenance of a higher concentration of mixed liquor solids to achieve the necessary food/micro-organism ratio. This point is similar to that made for lime treatment.

e. Adding alum reduced the rate at which oxygen is utilised in the aeration tank and increased that at which it could be transferred into the mixed liquor.

f. Adding alum increased the quantity of volatile solids produced per unit quantity of organics removed, giving more mixed liquor volatile suspended solids to be handled and treated in addition to the inorganic precipitates formed. Operating the plants at or below design flow produced 40-50% more dry sludge solids from alum treatment than from control, but the total volumes of sludge to be handled increased by only 25% due to the higher concentration with the alum sludges. When the plants were hydraulically overloaded the poor performance of the alum plant only increased the sludge production slightly compared with that from control.

g. Manually adjusting the alum dosing-rate daily according to the expected total flow was satisfactory and it was not necessary to allow for diurnal flow variations.

h. Return sludge pumping rates needed to be higher than those usually provided on activated-sludge works.

4.44. — (d) Work in Norway

4.44.1. Many small new wastewater treatment works are likely to be built in Norway and treatment methods are needed which will give good results under very variable loading and without highly skilled operation.

4.44.2. Oxidation ponds with their large capacity and simple operation might go far towards meeting those requirements. But chemical treatment for phosphorus removal is also needed to combat eutrophication in lakes and in long and almost land-locked fiords.

4.44.3. Nine identical experimental ponds each 0.9 m deep and having a surface area of 50 m^2 were used to investigate three combinations of oxidation and chemical treatment, each at three different flowrates. Detention times in the oxidation ponds varied from 29 to 2.7 days. They were generally fed with identical wastewaters.

4.44.4. Appendices A31 and A32 show results. Briefly: no chemicals were used in ponds 1, 2 and 3, in which detentions were 29, 13 and 3.3 days respectively, but the effluents were passed to subsequent settlement using alum doses between 154 and 185 mg/l. This mode is referred to as 'post-dosing'. 140-167 mg/l of alum were dosed directly into ponds 4, 5 and 6, which had detentions of 22, 8 and 2.7 days. This is referred to as 'pond-dosing'. Effluents from two-stage alum-aided settlement were fed into ponds 7, 8 and 9. This is referred to as 'pre-dosing'.

4.44.5. Unaided treatment in oxidation ponds was not really effective; even pond 1 with 29 days detention removed only 24% chemical oxygen demand, and nitrification was far from complete as 61% of the total nitrogen as 15.3 mg/l remained in the effluent. Longer detention did not necessarily increase removal; pond 3 giving only one-eighth the detention of pond 1 actually removed more chemical oxygen demand (33%).

4.44.6. Clearly pond-dosing should be the cheapest in capital cost of the three chemically-aided modes of treatment. The lowest detention of 2.7 days in pond No. 6 produced a good effluent containing only 89 mg/l chemical oxygen demand and 30 mg/l suspended solids although inferentially the SS of its feed appears to have been much higher than that of other ponds. Total nitrogen was reduced by only 20% but little nitrification could be expected in such relatively short-detention oxidation pond treatment. Even the 22 days detention gave little nitrification with 57% of total nitrogen remaining in its effluent. This pond may have tended to bulk sludge for its effluent contained twice as much suspended solids as the 2.7 days pond (No. 6) and more chemical oxygen demand (96 mg/l as against 89 mg/l). Therefore dosing ponds for short periods seemed most effective. Phosphorus removal at 89% was satisfactory.

4.44.7. Both post-dosing and pre-dosing gave results generally better than those from pond-dosing. Post-dosing seemed preferable to pre-dosing and pond 1 with 29 days detention gave the only effective nitrogen removal (82%, to 4.2 mg/l). Phosphorus was removed satisfactorily from all final effluents at all detentions.

4.44.8. Post-dosing should be the cheaper of the two modes as pre-dosing involves both primary (conventional) and secondary (chemical-aided) settlement. The 3.3 days detention post-dosing pond gave an effluent containing 16 mg/l suspended solids, 49 mg/l chemical oxygen demand and 21 mg/l total nitrogen — good when nitrification was not needed. Pond 2 giving 13 days detention only removed 21% nitrogen to 19.6 mg/l.

4.44.9. As the experiment was done during the summer it remains to be seen what effect severe Norwegian winter conditions would have. Conventional oxidation ponds are badly affected by extreme cold becoming little more than settling tanks.

4.44.10. In more temperate climates dosing 150 mg/l alum into a 2.7 days detention pond should give a reasonably satisfactory effluent, post-dosing the effluent from a 3.3 days detention pond with 175 mg/l alum should give a very good effluent, but post-dosing after a detention of about 29 days would be needed for reasonable nitrification.

4.44.11. Sludge production and quality were not reported but it might be inferred that the long-detention post-dosing treatment mode would produce little surplus or final sludge.

4.44.12. On the operational scale 150 mg/l alum was added to a sewer serving a community of 1800 persons 100m upstream of its discharge into an oxidation pond having a surface area of 3.7 m²/person. During a full year's operation the average removals were:

Suspended solids	81%
BOD_7 *	75%
Total nitrogen	34%
Total phosphorus	76%

*In Norway the BOD test is carried on for 7 instead of the more usual 5 days.

Remarkably the removals were better in winter than in summer. No performance results before alum dosing were available but the results shown were better than expected from conventional oxidation pond practice.

4.44.13. Extended-aeration activated-sludge works were both constant and batch dosed with 100-150 mg/l of ferric sulphate and of alum with reactor detentions of 24h or more. Results were good:

	7-day BOD		
	Feed (mg/l)	Effluent (mg/l)	% removal
Control (no chemicals)	348	14	96
Alum, 100-150 mg/l continuous dosing	295	5	98
Ferric sulphate, 100-150 mg/l continuous dosing	284	8	97
Batch dosing	296	6	98

Batch dosing was found easier than continuous dosing, and was subsequently installed using ferric sulphate at four army camps with excellent results. Phosphorus was removed well at all the chemical doses quoted.

4.45. — (e) Work in the United States

4.45.1. Many process arrays are possible when combining biological treatment which may be carried out using several process-methods and physical-chemical treatment of which an almost infinite number of variations is possible. The processes used and the order in which they are arranged depends on the characteristics of the wastewater to be treated, the type of effluent desired and on many other considerations such as space available for the plant and available operator-skills.

4.45.2. To date the United States has either tried out or adopted the greatest number of these possible variations. The table below shows process arrangements at eleven operational works, and the effluent standards required to be achieved. Abbreviations used are:

AS	biological activated-sludge treatment
TF	biological trickling-filter treatment
CAS	chemically-aided settlement
RECARB	recarbonation
MMF	multi-media or other mechanical filtration

BPC	breakpoint chlorination
CARBON	carbon adsorption
CHLOR	chlorination (for disinfection)

Lime was the chemical used most to aid settlement and usually to pH of 11 or above.

Serial	Works	Biological stage	Subsequent stages	Required effluent standard (mg/l)
1	Arlington	AS	CAS, RECARB, MMF, BPC, CARBON, rearation, CHLOR	BOD_5 under 3
2	Colorado	TF	CAS, MMF, CARBON	BOD_5 under 2
3	Dallas	AS	MMF, CARBON, CHLOR, reaeration	BOD_5 under 10
4	Fairfax County	AS	CAS, RECARB, MMF, BPC, CARBON, CHLOR	BOD_5 under 3
5	Montgomery	AS	CAS, RECARB, MMF, BPC, CARBON, CHLOR	BOD_5 under 3
6	Occuquan	AS	CAS, RECARB, MMF, CARBON, selective ion exchange, BPC	BOD_5 under 1 COD under 10
7	Orange County	TF	CAS, ammonia stripping, RECARB, MMF, CARBON, BPC, blending and storage	COD under 30
8	Los Angeles	AS	CARBON, CHLOR	COD under 12
9	Piscataway	AS	CAS, RECARB, MMF, stabilisation, CARBON, CHLOR	BOD_5 under 5
10	St Charles	AS	CARBON, CHLOR	—
11	South Lake Tahoe	AS	CAS, ammonia stripping, RECARB, MMF, CARBON, CHLOR	BOD_5 under 5

Appendix A33 gives further details of the flows and of carbon adsorption stages.

4.45.3. The Orange County effluent is injected into a groundwater supply, and that from the Montgomery County works is discharged to the Potomac River 20 miles above the water-supply intake for Washington DC. To preserve the clarity of Lake Tahoe, effluent from the 34,000 m^3/d works is pumped to a new artificial recreational reservoir in another catchment. A brief description of the Tahoe works will illustrate the complexity of operational advanced wastewater treatment works.

4.45.4. Conventional primary settlement is carried out in two tanks. Biological secondary treatment takes place in one of two systems of plug-flow diffused air reactors and completely-mixed mechanical aeration reactors, each followed by a secondary settlement tank. Lime is then dosed into the common effluents, followed by flocculation and settlement in two settlement tanks, removing much of the phosphate required to combat eutrophication in Lake Tahoe and raising the pH enough to convert ammonium ions to ammonia gas. The limed effluent is then pumped to the top of the ammonia-stripping tower and flows from the base to a collecting basin, whence it is pumped for two-stage recarbonation to pH 9.3 for calcium recovery in the first stage, and to pH 8.5-7.0, as desired, in the second. The recarbonated effluent flows to two balancing ponds in series, providing storage and equalising flows to subsequent treatment stages. Effluent is pumped from the ponds to tertiary treatment where is passes through multi-media filters backwashed with effluent drawn from the balancing ponds and eight carbon columns each containing 22 tons of granulated activated carbon. The effluent from the carbon columns is colourless, odourless and sparkling-clear. It is low in dissolved organics and thus has a very low demand for the chlorine used for final disinfection.

4.45.5. Carbon is regenerated when the effluent from the columns reaches either a COD of 15 mg/l or a Methylene Blue Active Substances (MBAS) detergents value of 0.5 mg/l. In practice this means regeneration of an effluent-throughput of 0.03 kg/m^3 of wastewater treated corresponding to a COD loading of 0.5 kg/kg carbon.

4.45.6. Primary and secondary biological sludges are centrifuged and then burnt in a 6-hearth gas-fired incinerator furnace to an insoluble sterile ash. Lime sludge is centrifuged and recalcined, and spent granular carbon is regenerated in similar furnaces.

4.45.7. Final effluent from Tahoe contains typically no suspended solids, 0.7 mg/l BOD$_5$, 10 mg/l COD, and 0.1 mg/l total phosphorus. Appendix A34 shows typical effluent qualities at the various treatment stages and Appendix A35 gives some design parameters for the South Lake Tahoe wastewater treatment plant.

4.46. — (f) Work in France

4.46.1. The difficulties of providing satisfactory and economic wastewater treatment for tourist areas where large and sudden variations in load arise have already been referred to in this Report. Under typical French resort conditions little land is available for works, smell and noise must be minimised and a good general appearance maintained.

4.46.2. For example, the resident design-population for works recently built at Bourgenay in the Commune of Talmont Saint-Hilaire, Vendée, was 400 and the summer population was 4000. Effluents to be discharged to adiacent sand-dunes were required to contain not more than 30 mg/l suspended solids and 70 mg/l BOD$_5$ in summer, and 30 mg/l suspended solids and 30 mg/l BOD$_5$ in winter. Conventional biological treatment was not considered suitable to meet those conditions.

4.46.3. During the peak holiday months of July and August the works provides chemically-aided settlement using alum, and dissloved-air flotation. During the other ten months of the year it gives extended-aeration biological activated-sludge treatment designed to deal with three times the load from the resident population of 400: that is from a population of 1200.

4.46.4. Wastewater is pumped to a 195 m^3 tank equipped with a 7.5 kW mechanical stirrer/aerator situated on the roof of a small office building. In summer this tank has a balancing role, the stirrer preventing sludge from settling-out. The wastewater passed from it over a floating weir and is pumped to a small stirred flocculating tank, where alum is dosed, and thence to the 7m^2 air-flotation unit.

4.46.5. The flotation process was tested extensively on industrial effluents before being employed on domestic wastewater. Air is dissolved into a sidestream of treated effluent by a patent static hydrocompressor at 4 bar pressure and the resultant liquid piped to the base of the flotation tank. The minute ascending air-bubbles lift suspended impurities and some colloids (already flocculated by alum addition), to form a thick scum or sludge on the tank surface.

4.46.6. Treated flotation tank effluent flows by gravity to an outfall in the adjacent sand-dunes. Sludge is skimmed automatically from the surface of the flotation tank at a dry-solids content of 7% to 9% and air-dried on beds after being consolidated and stabilised with lime.

4.46.7. In winter the 195 m³ elevated tank acts in an extended-aeration role, and fully-treated effluent passing over the floating weir flows by gravity direct to the sand-dune outfall. The surplus activated-sludge is thickened in the air-flotation tank, and is discharged to the drying beds after consolidation and lime treatment. The whole works, less access roads, occupies 670 m² of which 400 m² is taken up by the sludge drying beds, or abour 0.15 m² per head of summer population. It cost 790,000 Fr in 1977. Appendix A36 gives technical details.

5. Direct oxygen application

5.1. Technical background

5.1.1. Aerobic biological wastewater treatment is designed to increase the rate of natural processes in controlled conditions and under supervision. It brings the wastewater into contact with relatively high concentrations of micro-organisms in the presence of oxygen contained in the wastewater itself. Thus biodegradable organic impurities are oxidised to stable and less-objectionable forms; non-biodegradable substances are not changed.

5.1.2. Direct application of oxygen uses what is loosely called 'pure' oxygen, which is manufactured either elsewhere commercially and brought to site or on the site itself, in place of the oxygen from the air at the point of treatment.

5.1.3. Bio-degradable organic matter is oxidised at a rate related directly to the rate at which the oxygen dissolved in the wastewater is used by the micro-organisms, and possibly by the limiting rate of dissolving the oxygen. As air contains only about 20% oxygen, the use of 'pure' oxygen in its stead increases the rate at which oxygen can be dissolved — at similar temperatures and pressures — and correspondingly decreases the power required to attain any given dissolved-oxygen level whether by agitation, bubbling, or otherwise.

5.1.4. Other advantages claimed for direct oxygen application which result from method of use are referred to later. The 'deep shaft' technique which increases the rate of transfer of oxygen into solution without correspondingly increasing power requirements, is also referred to later.

5.2. Provision of oxygen

5.2.1. Commercial oxygen plants generally use the cryogenic method of production whereby air is liquified and oxygen separated from it by fractional distillation. The process can produce oxygen of 99.7% purity in quantities up to and beyond 1500 tons a day. Plants producing over 20 t/d require about 350 kWh of energy for each ton of oxygen.

5.2.2. A cyclical process known as pressure swing adsorption (PSA) has been developed since the 1950s in which a zeolite is used as a molecular sieve to adsorb nitrogen from air under pressure and which is then subsequently desorbed at atmospheric pressure for further use. Normally three zeolite pressure-vessels are provided; one adsorbing, one desorbing by release of pressure and purging with some of the oxygen product, and one compressing ready for its next adsorbing cycle. Capital costs are lower than for cryogenic plants for outputs up to 20 t/d but power costs are higher. Plants producing between 1 and 20 t/d require between about 600 and 350 kWh of energy per ton of oxygen depending on capacity and type of adsorbent.

5.2.3. Oxygen may be obtained by pipeline from a commercial plant or by a branch from an existing oxygen pipeline. Site storage refilled by road-tanker may suffice alone for small installations but some site storage is always desirable on all sites to provide for exceptionally high demands and during maintenance of site oxygen-production plant. Thus the direct application of oxygen involves reliance either on complex oxygen-producing equipment on site, or on the supply of oxygen from an external source. There are potential hazards in storing and using oxygen although strict observance of simple safety precautions should minimise them.

5.3. Review of processes

5.3.1. Applying oxygen directly has been used principally in the activated-sludge method of wastewater treatment. Oxygen activated-sludge (OAS) processes, as do conventional air activated-sludge (AAS) processes, require reactor tanks in which wastewater, micro-organisms and oxygen are brought into intimate contact. The 'mixed liquor' passes from the reactor tanks to settlement tanks and some of the sludge settled out is returned to the reactors to increase the number of micro-organisms. Most reactor tanks in air activated-sludge plants are open but most, not all, oxygen activated-sludge plants require them to be sealed to conserve oxygen and to reduce risk from, for example, fire.

5.3.2. Oxygen activated-sludge processes use several techniques for dissolving the oxygen in the wastewater by:

a. Agitating the mixed liquor and oxygen in a sealed reactor tank by rotating 'paddles' and similar devices.
b. Diffusing oxygen in fine bubbles into the bottom of a reactor tank, which may or may not be sealed, and often also agitating mechanically.
c. Injecting oxygen under pressure into a sidestream of mixed liquor abstracted from and returned to the reactor tank.
d. Injecting oxygen into a downflowing stream of mixed liquor to increase the residence time of the upflowing bubbles.

5.3.3. Applying oxygen directly can also prevent sulphides forming in wastewater. Sulphides are found only rarely in well-designed gravity sewers as the natural turbulence usually keeps some oxygen in solution and prevents the anaerobic conditions which encourage sulphides to form. They can occur in anaerobic conditions in pumping mains which contain wastewater out of contact with air. Hydrogen sulphide causes an objectionable smell when released to the atmosphers, attacks concrete, and corrodes iron and steel.

5.3.4. Injecting oxygen into a pumping main can prevent sulphides forming and can sometimes also partially but significantly treat the wastewater passing through, leaving a reduced load for the treatment plant.

5.3.5. Oxygen can be injected directly into tanks to reduce smell from anaerobic conditions and into ponds and streams to raise the dissolved oxygen levels and thereby protect plants and fish and reduce environmental nuisance.

5.4. Use in the activated sludge process — **(a) General**

5.4.1. In France two leading firms, Degremont in wastewater treatment and Air Liquide in oxygen production, combined to set up a research group, 'GIEDAL', for several pilot-plant studies during 1973-75 on the advisability of oxygen-activated sludge treatment of industrial wastewater, and on perfecting a French technique for European problems and methods of treatment. One of these studies on treating wastewater from the dairy industry was subsidised by the French Ministry of the Environment and the Financial Agency for the Rhine-Meuse basin. Other studies were carried out with the support of various indistrialists. In this way oxygen-activated sludge treatment was tested on wastewater from paper pulp factories, the plastics industry, dye works, a distillery, and on a mixed domestic/tannery wastewater. A full-scale treatment plant using both oxygen-activated sludge and air-activated sludge processes was set up later by the municipality at Dunkerque Grande Synthe.

5.4.2. In the Federal Republic of Germany investigations were carried out from 1972 onwards on a Union-Carbide oxygen activated-sludge pilot-plant at Wuppertal. This received government grant. Other work, including pilot-plant investigations at 15 different locations, was done to obtain design data for specific domestic and industrial plants. A special working group of Abwassertechnische Vereinigung — the water pollution control association of Germany — was set up in 1973

5.4.3. In the United Kingdom the government contributed to the costs of several pilot-plant investigations. These were Union-Carbide/Wimpey-Unox plants at Birmingham and Bath, an Air Products/Satec plant at Davyhulme, Manchester, and BOC/Ames Crosta plant at Rotherham. Subsequently the Wessex Water Authority constructed a full-scale Wimpey-Unox plant at Palmersford, Bournemouth on which further investigations are proceeding also with some government support. Work with a Marox/Farrer open reactor pilot-plant is proceeding at the Advanced Wastewater Treatment plant at Coleshill.

5.4.4. In the United Staes many full-scale plants have been constructed following extensive experimental work supported by the Environmental Protection Agency and we include information from them in this report. The wastewaters were predominantly domestic in origin for the pilot-scale work and the feeds to reactor tanks had been given conventional primary settlement. The oxygen reactor tanks were covered.

5.5. — (b) Performance (see Appendix A37 (Sections 1-16))

5.5.1. High levels of dissolved oxygen can be maintained more readily in oxygen-activated sludge reactor tanks than in those of air plants. For instance work at Wuppertal (Appendix A37/1) when oxygen and air plants were operated in parallel, showed 14-16 mg/l dissolved oxygen in the oxygen activated-sludge plant against 0.5-3.0 mg/l in the air plant (conventional air plants are normally run at 2 mg/l or less). The common feed with a BOD_5 value of about 210 mg/l contained effluents from chemical, foodstuff, dyeworks and metal-waste industries, and the effluents from both the oxygen and air plants generally had BOD_5 values of about 30-35 mg/l but the retention of 2 hours in the oxygen plant was only one-third of that in the air plant. Whilst about three times as much wastewater was fed to the oxygen plant as to the air plant the effluents were of about the same quality. Conversely, when retention times for both oxygen and air plants at Wuppertal were adjusted to 2 hours, the former reduced the BOD_5 of its feed from 348 mg/l to 18 mg/l in the effluent, the latter from 324 mg/l to 97 mg/l.

5.5.2. Similar reductions were confirmed by other experiments and notably that on a highly-industrialised wastewater at Manchester notoriously difficult to treat (Appendix A37/2) where only 1.9 hours detention in an oxygen plant reduced a BOD_5 of 248 mg/l in the feed to about 59 mg/l in the effluent; the effluent from the air plant in parallel had a BOD_5 value of about 112 mg/l. The open-topped pilot oxygen plant at Coleshill produced an excellent effluent with only 0.8 hours detention, but 2 hours detention was needed in the parallel air plant to give a similar product with a common feed of a weak domestic wastewater.

5.5.3. Both France and Germany worked on very strong sewage. Carcassing-house wastes at a Bavarian factory (Appendix A37/3) with a BOD_5 of 5655 mg/l — twenty times that of some domestic wastewaters — were reduced to effluents with a BOD_5 value about 111 mg/l by 60 hours retention in an oxygen activated-sludge plant. Liquors derived from a sludge heat-treatment plant in Berlin (Appendix A37/4) having BOD_5 values of 6000-7000 mg/l were reduced to effluents with BOD_5 values of 63-103 mg/l by 14-20 hours retention. In France, removals with high loadings of oxygen activated-sludge reactor tanks were:

Source of effluent treated	Load (kg $BOD_5/m^3/d$)	BOD_5 removal (%)
Dairy	4-5	96
Paper pulp	8-10	90
Plastics factory	5	95
Dye works	6	92
Tannery plus 20% domestic wastewater	3.75	91

Appendix A38 describes French work on tannery wastes.

5.5.4. The capability of oxygen activated-sludge to increase throughput of standard sized plants is best exhibited when industrialised and variable wastewaters are treated. The 'reservoir' of oxygen provided by high dissolved oxygen levels is particularly useful, especially where constituents harmful to the micro-organisms are present. But this advantage is not confined to such cases. At Munich (Appendix A37/5) a mainly domestic wastewater with a BOD_5 value of about 235 mg/l was given 1.9-2.4 hours retention in an oxygen-activated sludge plant to give an effluent with a BOD_5 value of about 12 mg/l. At Manchester (Appendix A37/6) domestic wastewaters having a BOD_5 value of 157 mg/l were reduced to effluents with a BOD_5 value of 11-16 mg/l by 2.5 hours retention. No parallel air trials were done in either case but it is likely that a conventional air plant would have needed about twice that retention time for the same reduction of BOD_5.

5.5.5. Most pilot-plants are fed with sewage at a constant rate and do not replicate the daily variations which occur at operational treatment works and consequently their results may be optimistic. However work on a pilot-plant at Bath which simulated daily variations in flow suggested that oxygen-activated sludge might not be particularly sensitive in this respect. This removed 81% of BOD_5 when treating a 'diurnally-varied' flow with a retention under 1.0 hour and 88% when treating a steady flow with a retention of 1.1 hours — only 7% more and with increased retention.

5.5.6. The ability of oxygen-activated sludge plants to treat more sewage than similar sized conventional air plants has been demonstrated but they are not necessarily economic on that account alone. It is clear that the final settling tanks need to be large enough to deal with the increased throughput to prevent excess solids being carried over in the effluent.

Experience in the United States showed that oxygen-activated sludge systems should be designed as an 'integrated package' consisting of a reactor tank, final settling tank, and sludge return facilities. These points need to be considered particularly when oxygen-activated sludge is is advocated as a simple means of 'uprating' existing air plants.

5.5.7. The phenomenon known as sludge bulking can effect the operation of conventional activated-sludge plants drastically; the activated-sludge in reactor tanks and final settling tanks occupies an excessive volume and can result in large amounts of solids in effluents. For instance, on the air/oxygen pilot trials at Coleshill, the open-topped oxygen plant worked satisfactorily on a biomass loading of 0.5 kg/kg, requiring a mixed liquor suspend solids (MLSS) of 6200 mg/l and a sludge return of 90% giving a net aeration time of 0.8 hours with dissolved oxygen at 2-3 mg/l. Under exactly similar conditions the parallel air plant failed to hold the MLSS, forming a large bulk of light sludge and consequently leading to excess solids in the final effluent. The general cause of bulking is far from fully understood and we cannot make any definite claim for oxygen activated-sludge in this respect.

5.6. — (c) Stability

5.6.1. This important quality associated with oxygen activated-sludge plants is thought to derive from the high dissolved oxygen levels used in them but cannot be demonstrated readily in simple figures. The following views have been expressed by experts taking part in the Study:

France: 'Instability is due mostly to variations in the potential settleability of activated-sludge; current experience indicates that using oxygen may reduce . . . this phenomenon . . . particularly . . . when the feed is rich is soluble carbonaceous compounds and when the installations are fed in a varying manner'.

Germany: 'The supply of oxygen to the reactors can meet the oxygen demand very quickly; therefore a good accommodation to fluctuations of the influent concentration is possible. Because dissolved oxygen is higher than with conventional aerators there is an advantage in using it for treating highly concentrated wastewaters'.

United Kingdom: 'There is evidence of robustness under fluctuating loads'.

United States: 'Another factor influencing the cost of oxygen systems was the relative insensitiveness of effluent quality to changes in . . . loading. Data accumulated from three well-investigated plants denoted consistent and impressive performance under stressed conditions'.

5.7. — (d) Nitrification

5.7.1. We gave much attention to this increasingly-important matter as it was often necessary to limit the ammonia content of effluents. This was achieved normally by increasing the retention time in conventional biological treatment until oxidation converted the nitrogen in ammonia successively to nitrites and then to nitrates, the latter being stable when discharged to receiving waters. Such 'nitrification' was promoted by particular micro-organisms in activated-sludge plants which are slow-growing and unable to survive low temperatures and low pH value in the wastewater. The optimum pH for nitrification is 7.5-8.5.

5.7.2. Oxygen and air plants in parallel, each giving long (7 hour) retention to a highly-industrialised wastewater from the Birmingham area containing 32 mg/l ammoniacal nitrogen (Appendix A37/8), produced very different effluents. The effluent from the oxygen plant still contained 32 mg/l ammoniacal nitrogen and had only 1 mg/l nitrate, whilst that from the air plant contained 5 mg/l ammoniacal nitrogen and 31 mg/l nitrate. The temperatures of the wastewater and the 'sludge ages' — a measure of the time allowed for the slow-growing micro-organisms to develop — were comparable.

5.7.3. The failure of the oxygen plant to achieve nitrification was unexpected and we tried several expedients including conversion to two-stage operation with an intermediate settlement tank but without success. The pH value of the effluent from the oxygen plant was lower than that from the air plant and in two-stage oxygen operation the pH values were lowered successively. When the feed contained less industrial effluent and the second stage was converted to air operation (Appendix A37/9) the pH values were successively 7.3, 6.8 and 7.2 and nitrification was achieved.

5.7.4. Work on a domestic wastewater at Bath (Appendix A37/7) confirmed these findings; nitrification was given readily by 1.0 hour retention in the first oxygen stage and 2.3 hours in the second air stage. Some nitrification was obtained in a single oxygen activated-sludge stage on a domestic wastewater at Manchester by dosing with sodium hydroxide to increase the pH value; detention time in the reactor tank of 5.8 hours was high but the wastewater temperature was seasonably low (Appendix A37/10).

5.7.5. French experts were also concerned at the difficulty of nitrification. They concluded like their United Kingdom counterparts that it was caused by carbon dioxide formed during the activated-sludge process being trapped in the gas-space between the liquid surface and the roof in covered oxygen plant reactor tanks and subsequently dissolving into the agitated liquid. The pH value was depressed to a degree which the nitrifying micro-organisms were apparently unable to tolerate. Work at Cons-le-Granville on dairy wastes treated in a covered oxygen activated-sludge reactor having three compartments in series showed (Appendix A37/11) that the pH was successively decreased from one compartment to the next. The relationships between pH and carbon dioxide concentrations in the gas-space (which reached 65%) were not simple and were affected by the buffering-capacity of the wastewater. Further work (Appendix A37/12) showed that the pH in the second compartment increased when this was opened and converted to air operation. French work also revealed that nitrification was attained with covered oxygen activated-sludge reactors treating paper-pulp wastes, tannery wastes and plastics-factory wastes which were all either alkaline or tending to alkalinity.

5.7.6. Nitrification was not required often in the United States. A large oxygen activated-sludge plant at Las Virgenes in Los Angeles succeeded in nitrifying in one covered stage (Appendix A37/13) but wastewater temperatures were high, loadings were low, and exceptionally large sludge ages (up to seventy-nine days) were used. The reactor cover was an inflated dome and not without its practical difficulties. Unfortunately the pH values were not recorded and there was sludge bulking during these experiments. Other work in the United States on a large pilot-plant at Blue Plains in Washington generally confirmed the nitrification results at Las Virgenes.

5.7.7. The experimental work reported briefly above represents one of the more conclusive achievements of the present initial advanced wastewater treatment study.

5.7.8. Wessex Water Authority's Palmersford works, the first public operational oxygen activated-sludge works in Europe, has a secondary air stage for nitrification purposes. Initial results on full load were very encouraging:

Parameter (mg/l)	Tank effluent	OAS effluent	Secondary aeration effluent
Suspended solids	113	12	7
BOD_5	138	20	9
Ammonia (NH_4-N)	41	26	3
Nitrate (NO_3-N)	–	10	26

5.8. — (e) Sludge settleability (see Appendix A37/1-16)

5.8.1. As mentioned previously, dewatering and finally disposing of the sludges derived from primary settlement and from the further final settlement following secondary biological processes can represent over half the cost of wastewater treatment. Sludge from settlement following air activated-sludge treatment is often difficult to dewater and the frequent claim that oxygen activated-sludge could be dewatered more easily was therefore important. Our work substantiated this claim in general but for reasons still mainly obscure to us.

5.8.2. The comparative work with oxygen and air at Wuppertal showed that the sludges from the oxygen plant settled about twice as fast as those from the parallel air plant (Appendix A37/1). Results from comparative work at Manchester (Appendix A37/2) were not so striking but the sludges from the oxygen plant always settled better than those from the parallel air plant.

5.8.3. French experience indicated that sludge settling times were 'always distinctly lower using oxygen than when using air' and United States experts found 'it was generally agreed that oxygen sludge exhibited excellent thickening properties'.

5.9. — (f) Sludge quantity (see Appendix A37/1-16)

5.9.1. Oxygen activated-sludge plants have been claimed to produce less secondary sludge than conventional air plants. These claims were important but our results varied too widely to enable us to either confirm or refute them. As so often in wastewater treatment, much depended on local circumstances and we found it difficult to draw meaningful general conclusions.

5.9.2. The comparative work at Wuppertal supported the claim. Values of 0.40 and 0.52 kg sludge/kg BOD_5 removed were obtained from the oxygen activated-sludge plant and 0.87 and 0.91 respectively from the air plant (Appendix A37/1). Although no other comparative figures for oxygen and air plants were available from German work the sludge production was low on all German plants. Values of 0.45 kg/kg BOD_5 removed were obtained on a domestic wastewater at Munich (Appendix A37/5). 0.31 and 0.35 respectively on an industrialised wastewater at Goppingen (Appendix A37/14) and as little as 0.09 on the Bavarian carcassing-house wastes (Appendix A37/3).

5.9.3. Some work in the United Kingdom on a difficult mixed industrial/domestic wastewater in Manchester showed a similar tendency when 0.6 kg/kg BOD_5 was removed with oxygen and 0.9 and 1.0 with air (Appendix A37/2). Not all results from oxygen activated-sludge plants were so convincing. A mixed wastewater at Rotherham yielded 1.0 kg/kg BOD_5 removal when feeds were generally weak but only 0.6 when feeds were stronger (Appendix A37/15). Experts in the United Kingdom felt that more work was needed to quantify the possible advantage of oxygen activated-sludge on this aspect.

5.9.4. The French felt that 'production of sludge when using oxygen is similar to that using air'.

5.9.5. The United States felt that 'available data indicated that oxygen systems probably produced less sludge than air systems at comparable . . . loadings (but) the exact quantity was still in doubt. Comparative data under similar operating conditions and on the same wastewater were needed'.

5.10. (g) Oxygen used (see Appendix A37/1-16)

5.10.1. Clearly the quantity of oxygen consumed is important in assessing the viability of oxygen activated-sludge treatment, and this varied considerably.

5.10.2. In Germany the quantities used were from 0.8 to 1.2 kg of oxygen for each kg BOD_5 removed when treating domestic and industrial waste feeds at Munich and Goppingen (Appendix A37/5 & 37/14) and 0.83 when treating Bavarian carcassing-house wastes with the high BOD_5 (Appendix A37/3). But the strong liquors from a sludge heat-treatment plant in Berlin required 1.52 kgO_2/BOD_5 (Appendix A37/4).

5.10.3. In the United Kingdom the corresponding quantities were 1.4-1.7 kg for domestic wastewater at Manchester (Appendix A37/6) but were lower at 1.1-1.25 kg when treating wastewater containing much industrial waste on the same site (Appendix A37/2).

5.10.4. More recent work in France on the versatile operational mixed oxygen-activated-sludge and air plant at Dunkerque gave about 25% saving in oxygen attributed largely to the avoidance of pH-drop associated with the introduction of an air phase.

5.10.5. Experience from experiments in the United States was extensive (Appendix A37/16). The oxygen consumption varied but it was felt that 'in the absence of nitrification, slightly more than one kilogramme of oxygen should theoretically be supplied for each kilogramme of chemical oxygen demand (COD) destroyed' and that 'generally, but nor always, less oxygen was consumed as plant loading increased'.

5.10.6. Appendix A39 gives recent information on oxygen activated-sludge plants in the Federal Republic of Germany.

5.11. Other uses of oxygen — **(a) Preventing sulphides forming in wastewater pumping mains**

5.11.1. Injecting 'pure' oxygen is only one of several possible means of combating the anaerobic conditions which cause sulphates in the wastewater in pumping mains to be reduced to objectionable sulphides. We can use other oxidising agents such as chlorine, sodium hypochlorite, and hydrogen peroxide or we can add nitrate which provides a source of oxygen alternative to that from sulphate. We need to consider each case on its merits after laboratory and site tests.

5.11.2. The amount of oxygen needed to maintain aerobic conditions depends among other things on the oxygen demand of micro-organisms in the slimes on the walls of the main and in the wastewater itself. Appendix A40 deals with this in detail.

5.11.3. Oxygen is usually injected immediately downstream of the pumps and techniques are well established. In the United Kingdom there are more than thirty operational installations, many on regional wastewater disposal schemes involving multiple pumping over relatively long distances to central treatment works.

5.12. — **(b) Treatment in pumping mains**

5.12.1. Although oxygen can be injected to combat anaerobic conditions in wastewater pumping mains little attention has been given to assessing consequent beneficial effects at the associated treatment works.

5.12.2. In the United Kingdom the work on this was done mainly at Bath where a 760 mm diameter iron main conveyed domestic wastewater from a large pumping station in the city to a biological trickling-filter works eight km away. The works, originally designed to treat a dry-weather flow of 16000m^3/d, was actually treating 24000m^3/d, and the suspended solids content and biological oxygen demand of the effluent often exceeded the required 30/20 standard. There was no room on site for more trickling filters and pilot-scale work had revealed difficulties associated with the anaerobic wastewater pumped to the works.

5.12.3. In 1975 oxygen equipment was installed at the pumping station to provide aerobic conditions in the main and a project funded partly by the Department of the Environment was set up to assess the effect on works performance.

5.12.4. Liquid oxygen from a storage vessel was vaporised and piped to fine-nozzle injectors on the delivery pipe from each pump. Gas was only injected when the pump concerned was operating. The quantity injected was set manually to provide a detectable level of dissolved oxygen in wastewater entering the works. A tracer technique was devised to identify 'plugs' of wastewater passing through the main.

5.12.5. As no parallel 'control' work was possible the programme included periods without oxygen injection for comparison but limited by the need to maintain satisfactory works effluents.

5.12.6. Appendix A41 shows outline results. Oxygen injection was clearly beneficial notwithstanding the effects of temperature and other factors.

The biochemical oxygen demand and suspended solids content of works effluent when averaged over each experimental period only exceeded the required 30/20 mg/l standard once. The suspended solids were then only 31 mg/l.

5.12.7. Appendices A41 and A42 show that injecting oxygen improved the effluents from primary settlement tanks at all rates of flow in both summer and winter. Like other treatment processes, it worked better with warm wastewater. Thus using it increased seasonal differences in the quality of effluent from both tank and works. Injecting during the summer removed on average in the primary tanks over 60% of BOD_5 from the incoming wastewater — a remarkable performance.

5.12.8. Injecting oxygen appeared to have little effect on both sludge quantity and quality.

5.12.9. Unexpectedly, injecting oxygen affected pumping in the main. All pumped flows fell during injection possibly because of gas-locking in the main as pressures rose but pump speeds did not change. At Bath the static head is low relative to friction head. The reduced output caused by injecting oxygen might be less marked elsewhere and this will be investigated. Appendix A43 shows daily power consumption against flow with and without injection. At high flows the power required during injection periods increased by about a third; at low flows by about two-thirds. Appendix A44 shows pressured variations in concentrations of dissolved gases and the composition of dispersed gases for the Bath pumping main.

5.12.10. The Wessex Water Authority as the responsible body propose retaining oxygen injection at Bath and have prepared a scheme for a supplementary pumping main as an alternative to extending the works using the activated-sludge process, to treat a dry-weather flow of 30000 m^3/d in the first stage of which half would be dealt with by the existing plant. Estimated costs are:

Effluent standard (mg/l)	With or without oxygen	Capital cost (£) (1977)	Annual running cost (£) (1977)
30/20 throughout the year	without	425 000	34 500
30/20 throughout the year	with	380 000	23 000
30/20 in summer) 50/30 in winter)	with	250 000	17 000

5.13. — (c) Combating smell

5.13.1. The hydrogen sulphide produced when anaerobic conditions cause sulphates in wastewater to be reduced to sulphides can give rise to nuisance from smell at wastewater treatment works. As already noted, injecting oxygen can prevent sulphides forming and hence can obviate or reduce smell.

5.13.2. Smell from hydrogen sulphide on one works in the United States fed by a 4.5 km pumping main having a retention of about 2 hours was eliminated by injecting oxygen at the pumping-station end of the main. Initially 30 mg/l oxygen was used but experience gained during six years successful operation enabled the dose to be reduced ultimately to 8 mg/l.

5.13.3. Smell from hydrogen sulphide at a works in the South of France served by two pumping mains was eliminated by injecting oxygen to a small contact unit on the works site having a retention as low as from 15 to 20 seconds. The former hydrogen sulphide concentration of from 5 to 10 mg/l was reduced to zero.

5.13.4. In the United Kingdom large new primary treatment works served by long intercepting sewers along the river valley are to be built by the Northumbrian Water Authority on the River Tyne at Newcastle, on a site at which it will be important to avoid any smell from hydrogen sulphide. Injecting oxygen into a sidestream of screened and degritted wastewater has successfully overcome this at other works in the Authority's area and they propose to install oxygen injection both at the new Tyne Works and at the major inverted-syphon sewer crossings of the river.

5.14. — (d) Uprating existing plants

5.14.1. Large and rapid seasonal variations occur in the quantity of feed to the conventionally designed activated-sludge works at the popular French tourist resort of Fouesnant. About 50,000 people may be in the town at peak holiday times during July and August where as the winter resident population is under 1000.

5.14.2. A supplementary 30m^3 sealed oxygen activated-sludge reactor was provided alongside the normal aeration tanks to uprate works performance. Mixed liquor from one of the normal tanks was piped to the supplementary reactor and oxygenated by a surface aerator operating in an atmosphere of oxygen provided from an adjacent storage tank. The main aeration tanks were covered to reduce noise and smell and to allow injecting oxygen into them during high-flow.

5.14.3. With the above modifications the works has produced a final effluent having a biochemical oxygen demand of 25 mg/l and a chemical oxygen demand of 80-90 mg/l with 80-90% oxygen utilisation, whilst maintaining dissolved oxygen levels of 8-9 mg/l in the supplementary reactor and 2 mg/l in the covered aeration tanks.

5.14.4. Following full-scale trials at Five Fords Works, Wrexham with the cooperation of B.O.C. and the Welsh Water Authority, oxygen injection was installed by the Wessex Water Authority at Holdenhurst works which serves much of the large seaside resort at Bournemouth. Oxygen was injected into a sidestream of primary tank effluent which was discharged into the mixed liquor in the activated-sludge reactors. Up to 5t oxygen/d uprated works capacity during the summer months by 25%, to 30,000 m^3/d, enabling a satisfactory and fully-nitrified effluent to be produced consistently. The works are close to houses and there had long been complaint of smell. About 0.5t to 1.0t oxygen/d injected into a sidestream of screened and degritted raw wastewater solved the problem.

5.15. — (e) Protecting natural and other waters

5.15.1. Various techniques including floating but otherwise conventional surface aerators have been used to augment dissolved oxygen levels in rivers, lakes and artificial waters, to preserve natural life and prevent smell. Latterly 'pure' oxygen has also been used, usually by injecting it under pressure into a sidestream of water from the source concerned.

5.15.2. 'Pure' oxygen entailing high running costs is unsuitable for permanent installations but may be useful in emergencies such as following accidental spillage of polluting substances into a river or seasonally. It might be an economical alternative to providing capital-intensive tertiary treatment processes only needed at peak periods.

5.15.3. The British Oxygen Company have established a mobile oxygenation service in the United Kingdom, used notably on the River Clyde when industrial action interfered with the operation of a large wastewater treatment works in Glasgow.

5.15.4. The French have used oxygen injection extensively and successfully to obviate smell from hydrogen sulphide from a flooded gravel pit being reclaimed by refuse tipping; the smell could be detected 20 km from the site. Aeration was tried without success — hydrogen sulphide was stripped from solution by residual nitrogen gas and aeration capacity was insufficient to keep the water aerobic. Smell ceased within 24 hours of injecting the oxygen, and sulphide in the pit water was fully oxidised within a fortnight.

5.16. — (f) Sludge digestion

5.16.1. 'Pure' oxygen has been used on pilot scale at the Ponthir works of the Welsh Water Authority to promote aerobic digestion in a covered reactor. It enabled digestion in the thermophilic range of 45°C to 65°C which needed only seven days detention. Conventional aerobic digestion is at lower temperatures and requires longer detention with commensurate greater power demand. The digested sludge was stable but its dry solids content was not particularly high; thus a large quantity of good-quality sludge was produced.

5.16.2. Pilot plant data from Ponthir and from two trials at Tonawanda, New York are:

		Tonawanda	
	Ponthir	I	II
FEED SLUDGE			
Total solids %	4.0	3.3	4.4
Volatile solids %	3.1	2.5	3.3
Temperature °C	12	24	17
DIGESTER			
Detention d	6.4	3.0	5.0
Temperature °C	53	52	50
REDUCTIONS			
Volatile solids %	29	30	40
Volatile acids %	64	—	—

5.16.3. Pasteurisation of pseudomonas and salmonellae species is claimed as a result of the high temperature of digestion, and the supernatant liquors are said to have relatively low BOD_5.

5.16.4. Full-scale trials at Speedway, Indiana, run at 31-33°C, with ambient temperatures between minus 2 and plus 8°C and with detention times ranging from 12 to 16 days reduced volatile solids by 43%-44% at loading rates of from 1.0 to 1.7 kg $BOD_5/m^3/d$.

5.16.5. Safety and structural aspects need to be considered carefully before adapting existing units to the oxygen-aided aerobic digestion process which operates at high temperatures than the units may have been designed for.

6. Other advanced wastewater treatment processes

6.1. Membrane Processes — **(a) General**

6.1.1. In recent years membrane separation techniques have been studied and developed primarily in connection with potable water. The systems have also been applied to wastewater treatment in some industries and processes.

6.2. — **(b) Reverse Osmosis**

6.2.1. The essential difference between reverse osmosis and most other membrane processes lies in the ability of reverse osmosis to remove dissolved ionic matter from solution. Reverse osmosis gives total ionic separation from the solvent whereas ion exchange merely exchanges ions. It uses applied pressure to reverse the well known phenomenon of spontaneous diffusion of a weak solution or solvent into a stronger solution through a semi-permeable membrane, which depends only on the nature of the material in solution and the temperature. In theory it is independent of the material properties of the membrane. In practice membranes are frequently cellulose acetate but sometimes other polymer formulations are used. They are not truly semi-permeable and may pass small amounts of dissolved materials. The amount passing through the membrane depends on both the membrane material and the processes used in its manufacture, on the type and concentration of the matter in solution and on the operating conditions in the reverse osmosis system. Appendix A45 illustrates the reverse osmosis process diagramatically.

6.2.2. Although high pressures may be desirable in theory for maximum flow there are practical limits. High pressure requires more energy and more robust and costly equipment and, for safety, more ancillary equipment. The membrane always compacts even with normal operating pressures resulting in gradually declining flow over the life of the membrane. Continuous high pressure accelerates compaction and causes irreversible distortion. Compaction effects apart, the flow may decline from membrane fouling due to deposition of blocking materials in the surface inhibiting transfer. This problem with reverse osmosis membranes is serious. Membranes also degrade chemically. Chemical cleaning can often clear fouled membranes but they will eventually degrade and have to be discarded.

6.2.3. For these reasons it is important to recognise that whilst reverse osmosis may remove suspended material it is not necessarily advisable to use it to do so. Suspended solids are certainly removed more cheaply by normal filtration.

6.3. — **(c) Ultrafiltration**

6.3.1. Ultrafiltration can be regarded as simplified reverse osmosis. The pore-structure of an ultrafiltration membrane of from 0.002 to 0.02 microns is more open than that for reverse osmosis and will retain macro-molecules but pass small molecules and ions. Ultrafiltration is primarily sieving and thus needs a lower pressure than reverse osmosis. This simplifies design and construction of the plant, reduces operating difficulties, reduces the rate of membrane fouling and thus the rate of decline of the flow with time. These ultrafiltration membranes still foul organically and thus block structurally, and also degrade chemically.

6.4. — (d) Electrodialysis

6.4.1. Electrodialysis applies an electric field across ion-exchange membranes to encourage the transport of ions of one charge in one direction and those of opposite charge in the other direction. Appendix A46 illlustrates an electrodialysis cell consisting of alternate cation and anion exchange membranes closely spaced and mounted between electrodes at each end. A potential difference across the electrodes causes cations to migrate towards the cathode and anions towards the anode but free movement can only take place through the respective membranes. This gives ion-enrichment and ion-depletion and thus produces solutions more and less concentrated than the original input in alternate compartments.

6.4.2. The ion exchange membranes are semi-permeable as they will allow passage of ions of one charge but not of the opposite charge.

6.4.3. The phenomenon of 'concentration polarisation' limits the application of electrodialysis. Ion-depletion occurs on one side of the membrane and ion-accumulation on the other because transport is faster in the membrane than in the solutions, limiting improvement in transfer without substantially increasing power consumption.

6.4.4. The accumulation of insoluble or ionically resistant matter can fould the membrane surfaces and result in loss of transport and of current efficiency. This fouling can be mitigated by reversing the polarity or cleaning with suitable chemicals in the feed but severe blockage may cause irreversible damage.

6.5. — (e) General views on membrane processes

6.5.1. Ultrafiltration can remove colloidal matter, macro-molecular particles, and other small materials including some bacteria and viruses difficult to filter by normal methods. It passes salts in true solution.

6.5.2. Reverse osmosis can remove all dissolved salts and most bacteria and other organisms. This suggests it is suitable for purifying water from poor quality sources or for following secondary or tertiary wastewater treatment to permit re-use of the water. It has potential for closed-loop recirculation recovery when accumulating dissolved solids are periodically or continuously removed.

6.5.3. Both these technologies concentrate solutions without using heat or chemicals. Thus they are attractive for recovering valuable concentrates which would degrade if heated and to which it would be undesirable to add chemicals.

6.5.4. Electrodialysis has similar application to reverse osmosis. It appears to use less energy at a lower dissolved salt level of 1000 mg/l to 4000 mg/l but reverse osmosis is better at levels above 4000 mg/l. Reverse osmosis has been studied much more extensively than electrodialysis for all kinds of saline water conversion in the United States.

6.5.5. Currently none of these processes show signs of being economic for treating domestic wastewater but they have advantages when either the concentrate is valuable or the water cannot be discharged and must be circulated in a closed loop.

6.6. Other Processes — (a) Imperial Chemical Industries Deep Shaft

6.6.1. This high-intensity biological process was introduced in 1974 for the purification of bio-degradable wastewater. Settled wastewater is circulated in a deep shaft with air and micro-organisms using the activated-sludge process. The deep shaft dissolves air efficiently, the micro-organisms are in long and intimate contact with the waste and treatment rates are higher than in conventional activated-sludge plants of the same volume. The flow of air is used to circulate the liquid/air/biomass mixture.

6.6.2. Appendix A47 shows the flow pattern. Wastewater is fed to the top of the deep shaft which is divided into up-flow and down-flow sections. Air is injected into the down-flow section at a velocity of from one to two m/s. As this velocity is greater than the rate of rise of the air bubbles, most of those carried down by the liquid are dissolved before they reach the bottom of the shaft. In the up-flow section, bubbles of dissolved nitrogen, residual oxygen and carbon dioxide are released and grow as the pressure falls. These bubbles escape to the atmosphere in a widened section of the shaft at ground level, the disengagement basin. The circulating liquid mixes with the incoming wastewater before going down the shaft again and treated liquid is drawn from the disengagement basin for settling out the solids.

6.6.3. The pressure at the bottom of the typical shaft might be between 10 and 15 bars. The bubble contact time is about 3 minutes. Turbulence is important for increasing oxygen transfer and for mixing the liquor. The shaft may be 100 metres to 300 metres deep (150 metres is normal). The diameter of the shaft may be one metre to ten metres and about 1.86 metres is normal. It produces less sludge than conventional aeration processes and this thickens more readily. The deep shaft can operate without primary sedimentation.

6.6.4. Two full-scale and three pilot-scale plants are operating in Europe with a further three full-scale and pilot-scale plants either contracted or under construction. There are five full-scale or pilot-scale plants either operating or being built in North America and four plants in Japan.

6.6.5. The process has been demonstrated as suitable for roughing treatment of wastewater before discharge to sea, for use where land is scarce and for treating strong bio-degradable organic wastes.

6.7. — (b) Denitrification

6.7.1. In 1970 the World Health Organisation recommended an upper working level of 11.3 mg/l nitrate in drinking water and a limit of double that concentration. Increasing amounts of nitrate — rich effluents reaching rivers and other sources of drinking water from either wastewater treatment plants or as run off from agricultural land are continually raising the nitrate content of drinking water in many parts of the world.

6.7.2. This problem has been investigated for many years, particularly at the Water Research Centre in the United Kingdom. Microbes capable of modifying their metabolism in the absence of free oxygen and using nitrate as an alternative oxygen source are fortunately common. They can be nurtured in carefully controlled regimes within filter systems or in activated-sludge plants through which the nitrate-rich effluent is passed. Modifying existing wastewater treatment processes to include a specific denitrification stage may be valuable. This may be a separate stage using filters or may be integral with a conventional activated-sludge process. In each case denitrification depends on the presence of sludge containing the living organisms capable of breaking down nitrate first into nitrite and then into nitrogen gas.

6.7.3. Practicable techniques include using anoxic zones in an activated-sludge plant, in submerged biological filters, and in submerged sandfilters; the second and third being examples of attached growth beds. In all cases a methanol feed is needed as nutrient for growth of the organisms.

6.7.4. Field scale trials using anoxic zones in an activated-sludge plant were made in the United Kingdom at Rye Meads Wastewater Treatment Works near Hertford. Using submerged biological filters was beset with problems connected mainly with adapting existing filters at East Hyde Wastewater Treatment Works near Luton. Methanol was fed to submerged sand filters at East Hyde Wastewater Treatment Works which gave better results than those obtained from activated-sludge plants using anoxic zones though the operational costs were much higher.

6.8. Reported Work — (a) Italy

6.8.1. In Italy a mobile pilot-plant containing ultrafiltration and reverse osmosis modules is being evaluated for treating different trade wastes. To date (May 1978) four wastes have been treated. These are effluents from a fibre finishing plant and an acrylic fibre manufacturing plant, wash-waters from a nickel-plating process, and the discharge from producing amide and its derivatives.

6.8.2. The mobile unit contains three different kinds of reverse osmosis and of ultrafiltration modules with their attendant pressurisation and regulation systems and a laboratory module allowing testing and characterisation of membranes of different permeability to identify the range of rejection values and operating pressures suitable for each effluent.

6.8.3. The object, insofar as the effluents from the fibre finishing and acrylic fibre plants are concerned, was to determine whether, with a high recovery factor, it is possible to obtain a concentrate economically disposable by incineration, and a permeate suitable for re-use or discharge.

6.8.4. Treating the effluent from a fibre finishing plant gave a product water suitable for re-use in the productive process, practically free from inorganic substances and organics other than surfactants at 13 mg/l. However the presence of surfactants rendered the water unfit for discharge as its level was well in excess of the 2 mg/l to 4 mg/l permitted under Italian law. Further treatment of the product water using activated carbon indicated that about 0.13 kg would be needed per m^3 of permeate to reduce surfactants to the required levels.

6.8.5. Assuming a membrane life of three years, the cost of using membrane techniques is indicated as competitive with that of any alternative biological process at 470 lire/m^3 (at 1974 prices). Further work is needed to confirm the assumed membrane life and to discover an alternative for pre-treatment or for disposal of the concentrate. The cost of incineration forms a significant part of the total treatment cost.

6.8.6. Effluent from acrylic fibre manufacturing plant contains acrylonitrile with sodium bisulphite together with traces of acetaldehyde, acrylonitryle and acetone, with a considerable quantity of sulphates, polymers, sulphites and oligomers. Preliminary investigations revealed that treating this effluent by traditional processes such as activated carbon, ion exchange resins, distillation, chemical precipitation, and biological treatments was either not feasible technically or was very expensive. It is necessary to oxidise thiosulphates and sulphites, compounds towards which membranes show low rejection, before treating in reverse osmosis modules. Here again, the product obtained was suitable for discharge or re-use in the production process. Capital and operating costs (1974) showed the cost of incineration, assumed at 5000 lire/m^3, as a substantial part of the total which varied, depending on the membrane used, from 403 lire/m^3 to 621 lire/m^3.

6.8.7. Chemically precipitating wash waters from electroplating generates large quantities of sludge containing heavy metal hydroxides which constitute a considerable disposal problem apart from the loss of water and heavy metals. Thus recovery is important economically and environmentally.

6.8.8. Formerly, the main difficulty in using membrane techniques for treating wash waters has been the need to control composition of the electro-deposition bath, thus precluding neutralisation before reverse osmosis made necessary by the narrow tolerance of cellulose acetate membranes to changes in pH. The advent of membranes with a wider operating range of pH removes this difficulty.

6.8.9. The object of these Italian experiments was to test the possibility, using reverse osmosis, of achieving recovery factors high enough to permit topping up the electro-deposition baths with the concentrate. Taken as a whole the tests indicate that this is possible. Further work is required on costs and membrane life, to determine the minimum recovery to be reached during treatment, the extent of accumulation of impurities in water circulating in a closed cycle, and to explore corrosion problems.

6.8.10. The mobile unit has also been used to evaluate ultrafiltration and reverse osmosis techniques for treating waste liquids from production of amide and its derivatives. At the test plant the most concentrated of the numerous flows making up the discharge are those from extracting and purifying amide and from using glucose in acid hydrolysis of the amide. Although comprising only 15% of the total flow they contain more than half the organic substances discharged by the factory. Thus, membrane techniques may make an important contribution as large quantities of raw materials may be recovered while at the same time reducing considerably the cost of treating the rest of the discharge.

6.8.11. A preliminary investigation revealed that ultrafiltration was the best technique. A literature survey showed that the principal problem encountered when using ultrafilitration to treat such discharges lies in the formation of a gel layer on the surface of the membranes which reduces their performance considerably. The tests carried out have shown that it is possible to treat amide effluent by ultrafiltration. Precipitates formed may be removed by washing with detergent solutions. However cellulose acetate membranes cannot be treated in this way and polysulphonic membranes were used for the washing tests. A two stage treatment scheme shows promise because in the second stage it is possible to maintain high specific production even using membranes with high rejection against organic solutes. This leads to the double advantage that recovery of raw materials is improved while reducing plant costs. Further tests are to be carried out to check the validity of the process and to obtain data necessary for cost analysis.

6.9. — (b) Netherlands

6.9.1. Very interesting innovatory work has been done by the Organisation for Applied Scientific Research (TNO) in the Netherlands.

6.9.2. Dynamically formed reverse-osmosis membranes have been developed, consisting of very small particles of cellulose acetate held in the pores of a containing tube. On a laboratory scale these membranes have been used to treat secondary effluent from a municipal treatment works and a polluted surface water. The retention of such membranes, referred to sodium chloride is about 85%. The membrane flux is about 1×10^{-5} m/s. The results obtained are considered comparable with those of commercially available flat membranes. The dynamically formed membranes have the advantage that fouling of them should not present a problem as recovery is possible without dismantling the installation. The membranes themselves are probably relatively cheap. These dynamically formed membranes do not require the intensive pretreatment of the effluent needed by conventional membranes.

6.9.3. Other membranes have been formed from water soluble polymers and have given retentions of the order of 85% — 90% referred to sodium chloride. Investigations of dynamically formed membranes have ceased as the economic prospects for using them on a large scale appear less favourable than was first thought.

6.9.4. Surplus liquid manure from cattle breeding areas can cause serious eutrophication problems. Following successful laboratory-scale investigations simultaneous phosphorus removal and biological purification of liquid manure from calf breeding stalls was studied on a larger scale in the field. Manure from 250 calves was treated semi-continuously in a $100 m^3$ tank as follows: Each day about 5 m^3 manure was added to the tank which was then aerated for about 20 hours. At the end of the aeration lime was added and mixed thoroughly and the contents of the tank were then allowed to settle. After settling, some 5 m^3 effluent was discharged to surface water. Removal of phosphorus increased with increasing pH of the effluent. At a pH of 8.5 a phosphorus removal of more than 98% was obtained leaving a phosphorus concentration in the effluent of about 2 mg/l. Adding lime to the aeration basin improved COD-removal and nitrification. The results are promising for removing phosphorus from calf manure and also from other phosphorous-rich agricultural and industrial waste waters. The additional cost of the lime treatment is estimated at 1.5 guilders per calf for the 6-month period it occupies a stall.

6.9.5. Two oxidation ditches of 500 population equivalent capacity, one as control, were used to investigate combined nitrogen and phosphorus removal in a low-loaded activated-sludge system. Lime was added to remove phosphorus in a simultaneous precipitation step; denitrification was biological. Nitrogen was reduced considerably even at temperatures as low as 10°C when 85% of it was removed. Removing phosphorus by the simultaneous precipitation step with lime was simple, cheap and efficient and with removal rates greater than 85%. More than 95% ofCOD was removed. Adding lime had no observed effect on the removal of COD. The effect of adding AVR, a commercial product containing aluminium sulphate and iron sulphate, on the removal of nitrogen, phosphorus and COD was studied. The use of AVR led to considerably reduced rates of nitrification: the observed values are about 60% of the rates when lime was added. The phosphorus concentration in the effluent ranged from 1 — 2.4 mg phosphorus/l. Also high doses of AVR did not lead to a lower phosphorus concentration. The addition of AVR had no noticeable effect on the reduction of COD.

6.9.6. A desk study was made to evaluate both technically and economically the production of activated carbon from sewage sludge and the use of this activated carbon to relieve the biological purification step. The study shows that the amount of carbon produced is too small to increase significantly the capacity of the biological purification process. Additionally, the cost of the process is high when compared with that of biological purification plus sludge incineration.

7. Economic evaluation

7.1. — (a) General consideration for advanced wastewater treatment

7.1.1. We can distinguish between economic and financial appraisal. Financial appraisal is concerned with cash, whilst economic appraisal is concerned with the full range of impact of an activity. Economic evaluation should include all resource costs rather than just financial costs. Economic evaluation should include external costs and savings but water authorities in the United Kingdom exclude them in their financial appraisals.

7.1.2. Experience in estimating costs generally has shown that when studying new products or processes we tend to underestimate the total cost so that new processes or projects appear more favourable or more economical initially than experience subsequently demonstrates. Some of the earlier reports on physical-chemical treatment illustrate this well. They did not include the cost of sludge treatment. A critical appraisal requires comparison of new processes with those to be superseded including any effects of inter-action. A simple flow diagram drawn at the start and including all process stages in both wastewater and sludge treatment helps to reduce errors.

7.1.3. Available costs for advanced treatment and traditional treatment should enable comparative economic appraisal either by cost-benefit or cost-effectiveness analysis. But like must be compared with like.

7.1.4. Costs used for this purpose must avoid distortion due to scale or due to differences in the quality of the influent. The effectiveness of advanced treatment varies with the quality of wastewater to be treated. Thus the estimated costs for treating domestic, industrial, and a range of mixed domestic and industrial wastewaters in varying proportions, by advanced methods should be compared with the cost of treating similar wastes by traditional methods.

7.1.5. Cost should be estimated in sufficient detail for consideration of all feasible combinations of processes. The limits of processes must be defined properly — to ensure like being compared with like and to enable costs to be allocated appropriately between processes.

7.1.6. Costs for economic evaluation should be measured in real terms and thus be free from the effects of inflation. This requires monetary values at any given time to be adjusted by multiplying with an index of price levels and expressing them in terms of a common base price level. Comparison of costs will otherwise be distorted by a change in the general level of prices. Outturn prices can be adjusted for inflation by dividing by an appropriate index of price level change. For example, if the cost of an item in a year is Cn and the price index has doubled between the base year and that year, the cost in base year prices is $\frac{Cn}{2}$. No hard and fast rule can be laid down about which index to use since appropriateness depends on the context.

Usable indices include those of input costs such as the British Electrical and Allied Manufacturers Association Index, tender prices such as the Directorate of Quantity Surveying Services Index and outturn prices such as the cost of New Construction Index. Evaluation of construction schemes requires forecasts of future costs in real terms — in some ways this is easier than revaluing known costs in money terms because if all forecasts are made in real terms there is no need to take account of future levels of inflation.

7.1.7. Identifying circumstances justifying the use of advanced treatment processes requires detailed estimates of capital and operating costs, and the estimation of external costs and benefits where possible. These include:

a. Capital costs of machinery and equipment, process structures and buildings, pipelines, land and ancillary works.
b. Cost of salaries, wages and fees for design, supervision of construction, commissioning, general management and administration to prepare the plant for use.
c. On-costs and establishment changes.
d. Operating costs including salaries and wages, costs of managing and maintaining the works in operation and the cost of chemicals and other materials.
e. Cost of services such as gas, electricity and transport.
f. Rates.
g. Loan charges.
h. External costs and benefits including things such as
    using sludge gas as a fuel
    increased value of sludge for disposal on land from using lime as a coagulant
    from the improved condition of receiving water course resulting from a higher quality effluent
    and from evaluation of other spillover effects such as changes in health risk, noise, odour nuisance and so on.

7.1.8. Some of the costs mentioned above are appropriate for financial appraisal but should not be included in economic appraisal, for example, rates which are a transfer payment. Loan charges are not an operating cost in the economic sense as resources are used-up when investment is actually undertaken. As financial analysis is concerned with cash flows of an authority, it takes no account of external effects which do not either generate revenue or incur financial costs to the authority. As economic analysis is concerned with all the effects of investment decisions it does take external costs into account.

7.1.9. Many external costs and benefits may be difficult but not impossible to measure in monetary terms. For example, advanced treatment using chemical precipitation can remove phosphates and a denitrification stage can remove nitrates. Discharging effluents not containing nutrients is not detrimental to the natural floral and faunal balance but the resulting lesser weed control would be a tangible benefit in monetary terms. Consequent on improved effluent standards, using the receiving waters as an alternative to a reservoir or borehole for a source of potable water supply could constitute a tangible benefit that could be expressed in monetary terms. Other benefits such as the use of water for recreation are less tangible and may prove impossible to express in monetary terms.

7.1.10. Various techniques have been used to try to evaluate spillover effects. One approach used questionnaires asking people to assess the value they place on an amenity. There is no material incentive for people to answer correctly and the reliability of response is difficult to assess. An alternative is to derive values from differences in property prices as attempted by the Roskill Commission for the Third London Airport but it is difficult to isolate one particular influence on prices. When monetary valuation is not possible the external effects should be listed with some possibly subjective estimate of their importance.

7.1.11. Estimating the cost of a full-scale advanced treatment plant presents problems. Directly scaling up all the costs from the pilot plant may not give a reliable figure. Equipment requirements may be derived from the pilot plant using performance relationships where equipment is similar to that used by conventional treatment. Costs can be estimated from data such as those contained in Water Research Centre Report TR61 (see also para 7.1.19). Performance relationships could be established for a variety of wastewaters so that costs could be estimated for treating different types of wastewaters to different standards of final effluent.

7.1.12. More precise definition of processes and consideration of all relevant costs are important. Particular problems arise from the disposal of sludge as the difference in quantity produced by the advanced and the conventional plants might vary with scale.

7.1.13. The capital cost of a treatment plant depends among other things on its capacity which is often decided on the basis of anticipated demand. The investment decisions are often taken at least four years before a plant is brought on stream.

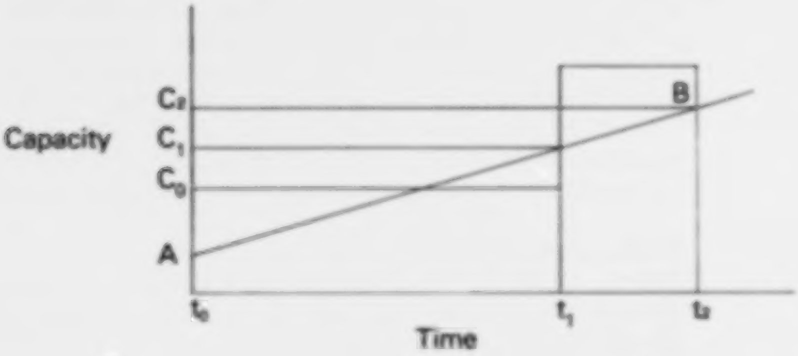
7.1.14. Estimating the cost of labour for operating the plant may be particularly difficult because it will be necessary to use more skilled labour, or to retrain existing staff for the more sophisticated operation and maintenance of advanced treatment units.

7.1.15. General trends in costs indicate advanced treatment plants to be usually more expensive than conventional plants of similar capacity. However, advanced treatment stages used in conjunction with conventional treatment may be cost-effective for relieving chronic overloading, for improving standards of effluent and for peak-lopping. Also they may reduce the cost of the excess capacity provided for intermittent use.

7.1.16. There may be scope for optimising the mix of capital costs and operating costs: it may be possible with other things remaining the same to reduce or increase recurrent expenditure on chemicals by using larger or smaller settlement tanks. Since operating costs (unlike capital costs) vary partly with throughput, the higher the ratio of operating to capital costs the greater the scope for variation in financial costs when the scheme is operating. Hence a decision on the optimal mix of capital and operating costs of the process involves taking some view on the value of flexibility. Even if advanced treatment is more expensive than conventional treatment it may be attractive because using chemicals can give a flexible response to overload.

7.1.17. Adding an advanced treatment stage to an existing plant may increase the capacity of the plant and hence possibly postpone heavy investment on major extension. Using advanced treatment stages intermittently may help treat the extra load during peak periods and avoid providing expensive capacity not used continuously and possibly causing problems with low flow. Cost savings from using advanced treatment can be evaluated by discounting future costs to a common base and comparing them with discounted costs of conventional treatment only. Appendix A48 illustrates this by a hypothetical example using discounted cash flows to estimate savings from advanced treatment.

7.1.18. Using advanced treatment in conjunction with conventional plant may reduce the excess capacity costs:



Line AB shows the volume of wastewater generated. The existing plant with design capacity C_0 will eventually become overloaded and it is proposed to investigate new capacity of C_1 at a time t_1. Using advanced treatment aids in the existing plant might enable it to continue beyond t_1, meeting the required effluent standard. Consequently, introducing new conventional capacity could be postponed until say t_2; alternatively the capacity required at t_1 might be reduced to C_1. Further work is needed to show whether the postponement of extensions on conventional plant would justify the cost of AWT.

7.1.19. The information in this section should be supplemented by reference to the following Water Research Centre Publications:

a. Cost information for water supply and sewage disposal (TR61) giving capital cost data and cost functions — November 1977.

b. An economic assessment of in-sewer treatment methods — Spring 1978.

and to the Sewage Treatment Optimization Cost Model, referred to as 'STOM', and now being developed under control of the Water Research Centre assisted by an external advisory committee.

7.1.20. Appendices A49/1 to A49/4 and A50 to A54 give costs of advanced treatment provided by the Co-Pilot countries.

7.2. — (b) Application to oxygen activated-sludge

7.2.1. We must know the capital and running costs of both the oxygen and the air processes to compare them. We have some information on the air process in its various forms but little for operational oxygen plants, at least in Europe.

7.2.2. Often other than economic factors have to be considered, as at Palmersford where site restrictions and the need to minimise smell were powerful inducements to adopting an oxygen-activated sludge plant. The Wessex Water Authority estimated the aggregated capital and running costs of this 4,500 m^3/d oxygen works to be marginally less than those for an equivalent air plant even though a supplementary air-activated sludge stage was provided after the oxygen reactors to give a fully nitrified final effluent.

7.2.3. Producing oxygen on site on all but the smallest works (where it would be neither feasible nor economic) provides the choice between the cryogenic and the pressure swing adsorption (PSA) processes. For oxygen outputs over 20 t/d the capital costs of cryogenic plants are likely to be less than those of PSA. Running costs for both types of plant are dominated by the energy consumption; a cryogenic plant uses about 350 kWh/t of oxygen produced and a PSA plant between 360 and 600 kWh/t depending on the effect of the type of adsorbant used on the size. The larger the plant, the less the unit power consumption. Though adsorbants are expensive they are reported to have a long life with efficient plant operation.

7.2.4. Site storage of oxygen maintained by mobile tankers is always needed even if only as a reserve and this increases the cost of the plant.

7.2.5. Our experience has shown that oxygen plants can operate with smaller capacity reactor tanks than the conventional air activated sludge plants. Nevertheless we need more work on a pilot-scale before we can decide with any confidence on the tank capacity required. In estimating the cost of oxygen plants we must remember to include the extra cost of covering the reactor tanks.

7.2.6. The running cost of the reactor tanks is dominated by the energy consumed. The energy needed to dissolve a fixed amount of oxygen into the wastewater in oxygen systems is less than that needed by air systems but both processes use energy to mix and to maintain the activated-sludge in suspension.

7.2.7. Data from the United Kingdom indicates that the energy required by oxygen reactors varies from about 300 kWh/t of oxygen dissolved in the usual sealed type to 400 kWh/t in those using the side-stream principle. Requirements for air systems vary from 500/700 kWh/t in surface-aeration and normal diffused-air reactors to perhaps 1200 kWh/t in the relatively rare 'coarse-bubble' installations. However these figures for air plants all assume zero dissolved oxygen in reactor mixed-liquor. The energy to maintain the usually desirable 1 or 2 mg/l of dissolved oxygen would be rather higher. To achieve the 50% of the normal air saturation concentration approached by most oxygen plants might double the normal energy needed for an air plant.

7.2.8. Thus with oxygen produced by the PSA process the total energy consumed by a sealed-reactor oxygen plant using 1.0 t/d and 20t/d oxygen might be 900 kWh/d and 660 kWh/d respectively. However, during initial running at Palmersford using only 1.1 t/d of oxygen from a pressure swing adsorption plant capable of 1.8 t/d, the total energy to treat 4780m^3/d of domestic wastewater was 1693 kWh/d.

7.2.9. That sludge dewatering and disposal may account for half or more of the total cost of wastewater treatment is well known. We have also referred to the difficulty of dealing with the sludge derived from biological secondary processes.

7.2.10. The quality and quantity of sludges from oxygen-activated sludge plants were considered earlier and many such sludges seemed to settle and dewater well. Good settleability would imply smaller final settlement tanks for any given throughput with consequent, if marginal, saving in capital cost. Good dewatering quality and reduced quantity of sludge were reported from some experiments but pilot plant work is needed in each case before sludge treatment is designed for operational oxygen works. Significant savings in both capital and running costs could ensue from the better characteristics of sludge from the oxygen process.

7.3. — (c) Views from France

7.3.1. French workers have carried out extensive experiments with oxygen-activated sludge plants treating numerous industrial effluents and domestic wastewaters. Their views on the economic aspects of oxygen-activated sludge are outlined briefly below.

7.3.2. Capital cost would be reduced by using smaller reactors and final settlement tanks although less would be saved in continental Europe, where capacities in conventional activated-sludge plants have been traditionally relatively lower than in the United Kingdom and the United States.

7.3.3. These savings would be insiginificant at small works, but could be material at works treating industrial wastewaters with an easily-bio-degradable BOD_5 of about 1000 mg/l or more, or at municipal works with a BOD_5 load over 3000 kg or serving a population exceeding 50,000.

7.3.4. The better settleability of the oxygen process sludge could be a considerable advantage if it was conditioned thermally but less so if it was conditioned chemically. Whilst French work did not show a reduction in sludge quantity, any found would be an important argument in favour of oxygen-activated sludge plants.

7.3.5. Running costs of oxygen plants were unlikely to be less than those for comparable air plants.

7.4. — (d) Views from the Federal Republic of Germany

7.4.1. A decision to install an oxygen activated sludge plant should take account of its advantages over the air process, namely:

a. less space needed
b. high oxygen availability and adaptability to fluctuations in load
c. less odour
d. less noise
e. less sludge produced which is also easier to dewater.

The reasons for selecting oxygen varied for the six existing industrial and four under construction or proposed municipal plants. Oxygen was selected for the first municipal plant at Göeppingen because space was limited; for that at Bremerhaven for a combination of reasons; and for that at Bonn because of limited space and the need to reduce odours.

7.4.2. The space needed for an oxygen activated plant is assumed to be about 20% to 50% of the necessary tank volume of an air activated sludge plant to provide an effluent of the same standard. The permissible sludge load can be about double that of air plants. Experience has shown the advantages of oxygen plants to be greater in treating trade and industrial wastes than for municipal effluents.

7.4.3. Data from ten plants shows that a single stage oxygen plant has a BOD_5/kg performance comparable with that of an air plant of about 0.15 kg BOD_5/kg of dry sludge per day. With a sludge loading of 0.5 kg BOD_5/m^3/d the space needed would be reduced to about one third. The space saved using oxygen compared to a two stage plant, where that is necessary for high loading, would be even greater.

7.4.4. Compared with air plants there are significant power costs with oxygen plants both for feeding and producing the oxygen. It is also necessary to differentiate between the two types of oxygen generating plants; the low temperature or cryogenic plant and the adsorption plant. Whilst cryogenic plants are more efficient they cannot be, or could not until recently, be controlled as readily as smaller plants. Using the nitrogen obtained during the generation of oxygen at Wuppertal is exceptional.

7.4.5. The power needed to produce oxygen depends on:

a. the generation process (cryogenic or adsorbtive)

b. the purity of oxygen

c. the state in which the oxygen is supplied, whether gaseous or liquid

d. the size of the plant, the daily production and the plant loading.

7.4.6. The specific energy required for cryogenic plants falls as the quantity produced and the loading increases, and rises as purity increases. The liquifaction of gaseous oxygen requires additional energy. Energy is required in adsorption plants essentially for conveying air through the molecular sieves and the size of the plant or the quantity produced have little influence on the specific energy used.

7.4.7. In Germany average values of power required for the production of oxygen are 0.45 kWh/kg O_2 for adsorption plants and 0.35-0.37 kWh/kg O_2 cryogenic plants although the latter figure may approach the value of 0.343 kWh/kgO_2 which is the value used in the USA.

7.4.8. The power required for oxygen feed varies from 0.197 to 0.221 kWh/kg O_2 corresponding to an oxygen yield of from 5.1 to 4.5 kg O_2/kWh.

7.4.9. The total power needed to produce and feed oxygen to the activated sludge tank is the main interest and differs considerably between the two types of oxygen production. If the oxygen is produced in an adsorption plant the power consumption is around 0.72 kWh/kg O_2 and if a cryogenic plant is used it is about 0.58 kWh/kg O_2.

7.4.10. An oxygen yield of 1.5 to 2.0 kgO_2/kWh is appropriate to a well designed and adjusted aeration installation. The specific power consumption is between 15.4 and 11.5 kWh per person per year for a sludge load of 0.15 kg BOD_5/kg dry solids per day and between 10.9 and 8.2 kWh for a sludge load of 0.3 kg BOD_5/kg dry solids per day. It has been suggested that about 3 kWh per population equivalent per year for other uses should be added to obtain the total power consumption of a sewage works. The specific power consumption per person per year is no higher than in air plants with the same sludge load whilst the decomposition within the oxygen process is greater.

7.4.11. Oxygen generating plants are extremely reliable and require little maintenance but a routine service involving a total shut down of six days is recommended every two years. This gap has to be bridged by supplies of liquid oxygen. Very volatile combustible substances such as benzine can accumulate and safety devices are needed to continually measure the hydrocarbon content of the effluent and if necessary switch off the oxygen supply and purge the oxygen from above the sewage.

7.4.12. In comparing oxygenation with aeration it is necessary to compare annual costs, taking into account capital costs, and any significant variation in costs between treating the sludge and the exhaust gases.

7.4.13. The capital costs for the biological stage with secondary clarification were around DM 8.2 million at Göeppingen where site conditions were difficult. The specific costs for the activated sludge tank including the oxygen generating plant are DM 949/m^3 for a tank with a volume of 6,270 m^3.

7.4.14. The probable capital cost of the Breisgauer Bucht plant was DM 80.8 million. A comparable cost for diffused aeration was DM 86.2 million and for surface aeration DM 78.3 million, so the oxygen plant comes between the costs for the two types of aeration plants. The specific costs for the activated sludge tank with a volume of 24,400 m^3 are estimated at DM 763/m^3 including oxygen production. The costs of oxygen production vary between DM 5.7 million and DM 7.5 million.

7.4.15. A cost comparison for Bremerhaven showed that the capital costs for the plant with oxygen were approximately 20% lower than with air.

7.4.16. Specific costs of DM 525/m^3 of the activated sludge tank have been calculated for Bonn excluding the oxygen generating plant. It is necessary to vary the oxygen production in the ratio 1:4 during the day thereby requiring a more expensive plant, so that the costs of the activated sludge tank including the cost of oxygen production is about DM 1,000/m^3.

7.4.17. The capital costs of DM 79 per population equivalent per year at Wuppertal are relatively low if it is borne in mind that the whole plant, including the aeration equipment above the activated sludge tank and the settling tank, is covered. The specific costs for the activated sludge tank are shown in figure 1 in Appendix A with cost curves for oxygen and air activated sludge tanks but it should be noted that the space loading with oxygen can be from two to five times greater than with air. Although the costs related to space are higher with oxygenation that does not mean that overall costs are higher.

7.4.18. The capital costs of oxygen generating plants compared with the oxygen provided are shown in figure 2 in Appendix A.

7.4.19. It is too early to comment on the operating and annual costs under German conditions on the basis of operating data; although probable annual costs at Bremerhaven were estimated 7% lower for oxygen than for air.

7.4.20. The operating costs of around DM 10 million per year at Wuppertal are not thought to differ widely from those of an air plant.

7.4.21. Oxygen plants achieve the same purification efficiency as air plants when they have twice the sludge load and three times the space loading of the latter.

7.4.22. By comparing costs for plants to serve population equivalents of 100,000 and 500,000 persons it was concluded that the costs for air and oxygen activated sludge plants differ very little even if unfavourable assumptions are taken for oxygen such as ignoring the easier dewatering properties of the sludge. Whilst construction costs for oxygen plants are slightly higher than for surface aeration plants this disadvantage can be reduced by selecting a different type of aerator. Cost curves for sewage works with aeration and with over 90% removal of BOD_5 are shown in figure 8 and it can be assumed that the costs of using oxygen correspond roughly with those using air.

7.5.23. Each individual case should be considered on its merits and if the particular advantages of the oxygen process can be utilised then these should be considered in the plant design as they are likely to lead to lower costs.

7.5. — (e) Activated carbon

7.5.1. The cost of activated carbon treatment varies according to the process used and the waste being treated. The lower the strength of effluents applied to it, the longer will be the life of the carbon before exhaustion. There is very little published information on costs. However a comparison can be made between granular and powdered activated carbon treatment in independent physical-chemical systems based on cost information provided in a relevant Environmental Protection Agency publication. Appendices A50 and A51 show the estimated costs of carbon treatment for a 37,850 m^3/d plant. Data for the powdered carbon system are presented for both regeneration of the carbon and for its use on a throw-away basis. The figure 3.4¢/m^3 for granular treatment is slightly lower than that of 3.8 ¢/m^3 for powdered carbon at a dose of 100 mg/l but it must be pointed out that a very large contingency of 50% has been allowed in the powdered carbon system capital costs. Accurate comparison of the two treatment systems will have to await full-scale use of powdered carbon.

7.6 — (f) Regeneration of activated carbon

7.6.1. Some costs of carbon regeneration are given in most published material on the subject. Comparison of different processes is difficult as carbon usage will vary according to the wastewater and the adsorption and regeneration systems used. The size of the wastewater plant has been shown to have considerable effect upon the overall costs of regeneration. The amount of fresh carbon purchased to replace losses has a marked effect on the overall costs, and more so as the size of the plant is increased.

7.6.2. The costs of regeneration by multi-hearth furnaces and rotary kilns are reported to be about the same. Whilst the purchase price of the multi-hearth is higher, installation costs are lower. One major conclusion from Hutchins' 'Thermal Regeneration Costs' is that when less than 260 kg of carbon is used it is generally more economical to have the carbon regenerated by the manufacturer rather than to regenerate on the site or to discard it. Appendices A52 and A53 are taken from this publication. Appendix A52 gives operating costs of regeneration including amortization, and allowing for 7% make-up carbon in each regeneration cycle. Appendix A53 gives the effect if the make-up was increased to 10%. The resulting percentage increase in costs can vary from 2.8 for small plants to 38.5 for large plants.

7.6.3. A regeneration capacity of 900 kg/d is considered to be the maximum for full operation of the smallest commercially available furnace. Comparing the total of $0.26/kg for this plant with fresh carbon purchased at $0.75/kg, the advantage of regeneration on site is clear.

7.6.4. No published data is available for the cost of regenerating by rotary kiln; there are only a few in operation. However operating costs have been estimated as about the same as those for multi-hearth regeneration but maintenance costs may be lower.

7.6.5. No full scale powdered carbon regeneration system has yet been in operation in the wastewater field for any length of time. Costs are therefore very much estimates. Appendix A54 gives estimated regeneration costs for a fluidised bed furnace with various carbon losses. It should be noted that regeneration losses may be higher than for granular carbon. About $9.9/kg could be a reasonable estimate for this system.

8. Setting the study in the 1978 context

8.1. — (a) Introduction

8.1.1. At this appraisal stage in the Report we could usefully review the general state of the art of treating wastewater as a prelude to advising how to apply the results of the Study to improve wastewater treatment generally. To place advanced treatment — which encompasses our recent work — in its right context we must first remind ourselves, albeit briefly at this stage, of the basic philosophy of wastewater treatment, and develop the background introduced in chapter 4.41.

8.1.2. In the beginning, why do we treat wastewater at all? What is the underlying purpose, what are the objectives? How can we do it, when should we do it, where in the water cycle should we do it? Who should do it for whose benefit at what allowable cost? We should certainly be quite clear we know what we are trying to do before we first investigate what can be done and then decide how best to do it.

8.2. — (b) Background

8.2.1. For this purpose we describe wastewater as the liquid wastes of an urbanised community. It usually contains the waste products from humans and their life style, the wastes from local industry, fortuitous wastes such as groundwater and rainwater, and occasionally extraneously introduced substances alien to the normal water cycle.

8.2.2. Apart from the transporting water which usually starts as potable quality and comprises about 99.9% of the flow, the pollutants can be either organic — which can themselves be either bio-degradable or non-bio-degradable — or non-organic which are often non-bio-degradable and sometimes mineral.

8.2.3. These impurities can be in either physical suspension, colloidal dispersion or true solution in the transporting water. Normal domestic wastewater usually has pollutants in all these states.

8.2.4. Accepting that our present way of life and water carriage sewerage will continue into the foresseable future to generate large quantities of wastewater for treatment we must direct our treatment to rendering that wastewater acceptably innocuous before discharging it to the environment. We must then dispose of it without danger to health or damage to amenity and at a cost acceptable to the public at large.

8.3. — (c) Action

8.3.1. We must aim by good planning, design, construction, management, and operation to avoid risk to health and offensive smells from putrescent wastewater residues which may lead to exaggerated complaints of more general nuisance. We must aim to prevent eutrophication and thus excessive weed growth in our inland waters by restricting the discharge of nutrients such as nitrates and phosphates in our effluents. We must avoid pollution of our land or water with objectionable residues from treatment, for example we must prevent pollution from sludge. We must not allow unrestricted passage to any dangerous or foreseeably dangerous substances, particularly possible carcinogens such as those from tars and other bituminous residues and possibly nitrates. They must not be allowed to pass through our wastewater treatment plants into receiving waters, with their not unlimited capability for natural purification, from whence they could pass through potable water intakes, gain access to public supply and thus pose health hazards for our people. We think micropollutants are probably a significant hazard and these include organic substances and derivatives from heavy metals such as for example cadmium, lead and mercury. In the United Kingdom we are presently concerned particularly with organo-halides — for example from pesticides. These often migrate to the sludge and thus may be ingested by animals or absorbed into the soil and groundwater and thence into plants. Residues from water-soluble paints may be dangerous.

8.3.2. Apart from the hazards to humans and animals we must aim to protect our countryside for itself. We must safeguard our fields, ponds, streams, rivers and hence the origins of most of our water supplies. We must keep our bathing beaches and coastal waters safe for our recreational enjoyment and for commercial use.

8.3.3. By implication this might in the limit entail either removal, reduction or modification of all substances in wastewater likely to be injurious either to man or to his eco-system though we think this extreme is unlikely. And — most importantly — absence of existing and obvious nuisance is no guarantee that no danger exists either at present or for the future.

8.4. — (d) Tasks

8.4.1. Clearly the first and probably the major task is to decide what substances in wastewater pose problems for us, both immediately and no less importantly from longer term contact with sub-clinical concentrations of the toxic materials or even the residues from treatment. Our first concern must be for people but we must also have regard for the wellbeing of animals and crops, and all the other necessary things in our ecosystem on which we rely for survival. We should also aim to pressure the desirable things on which we found our recreation and enjoyment of life to encourage this survival.

8.4.2. When we have identified the substances to be dealt with — and much remains to be done even on this preliminary stage — we must then attempt to allocate priorities for action. Which substances should we deal with first? With what urgency? What residual risks are acceptable? And at what cost? Much needs to be done. How should we proceed more expediently in this particularly difficult area of identifying and priority rating hazards when, for example, medical colleagues are naturally — and justifiably — reluctant to predict likely dangers and raise possibly unnecessary fears before they have adequate evidence?

8.4.3. There is a well known relationship between water quality and the risk of cholera, typhoid or hepatitis infection. But we have insufficient indication of the degree of risk from drinking water containing even small quantities of pollutants to make an informed judgement on the justifiable investment in investigatory work. Even advice on the use of new chemicals in industry can only be tentative at this stage.

8.4.4. To the informed layman there appear to be obvious dangers from all pathogenic organisms carried in the water cycle, from the dissolved compounds of most metals, particularly of heavy metals such as lead, mercury and cadmium and from other things not naturally there. He is suspicious of steroids and sex hormones and tar residues. He suspects there may be dangers from organohalides such as chloroform which may be formed during the water treatment process and from newer compounds such as the polychlorinated biphenyls discharged by some higher technology industries. All these substances may also affect the soil and crops on land either irrigated with the polluted water or nurtured with the separated sludge.

8.4.5. Because we are re-using water to an increasing extent we should bear in mind the substances suspected of being hazardous when present in drinking water. Our wastewater treatment and disposal should avoid increasing and should if practicable reduce the quantities of those possibly undesirable substances in our surface and underground waters.

8.4.6. Whilst many of the standards recommended for drinking water may be founded on prudence and natural caution rather than on conclusive evidence they can still be a valuable guide. The complete removal of all pollutants from wastewater is probably not necessary, and is certainly not practicable even if it were possible. And we are not even sure that prolonged drinking of chemically pure water, devoid of even trace materials, is not in itself a health hazard.

8.4.7. Notwithstanding this difficulty of identification and selection we must in prudence develop wastewater treatment technology and methodology to permit us to remove or modify hazardous substances either known or suspected to be present in wastewater and which cannot be otherwise removed — for example by improved control over discharges to sewers. We can then use our capability most profitably and as the occasion demands.

8.5. — (e) Implementation

8.5.1. When the need for removal arises it should be met in the best way available. The process could be optimised on consideration of cost, energy, resource, design, construction, operation, management, maintenance, risk reduction and other things. Many say we should use the most cost/effective solution.

8.5.2. The present mechanical/physical processes for removing gross solids and floating matter by screening and skimming are satisfactory. Whilst the principles and plant could be developed and automated they provide no obvious scope for chemical aids or other advanced methodology.

8.5.3. The current process of quiescent settlement by gravity to remove the heavier suspended solids is cheap, effective and simple. Whilst some process and plant development is possible it is likely to be of limited benefit. Chemical aids to improve settlement show great potential. Although they usually increase the cost they may often improve the cost/effectiveness of this undoubtedly useful primary settlement process. Further development is likely to enhance the performance and it is unlikely to be replaced in the near future by a higher technology process such as microstraining.

8.5.4. The process of biologically oxidising suspended, colloidal and dissolved impurities with either activated sludge reactors or percolating filters with either natural or man-made media is effective in lowering the oxygen demand of the wastewater by degrading at least the bio-degradable element. Considerable process development for example by increasing the treatment rate may be feasible, equipment may be made more sophisticated, and automated control may be used. Whilst the substitution of commercial quality oxygen for natural air may be advantageous in some circumstances, present knowledge suggests that other chemical aids are unlikely to be of any significant help. We see the development of processes producing little or no sludge for disposal as highly rewarding and certainly so if it can be done at competetive cost.

8.5.5. Ways of settling the solids formed by this biodegradation can presumably be improved in the same way as for primary settlement in spite of the different settleability of the sludge. Surprisingly this has attracted little separate attention so far.

8.5.6. When fed with a good quality secondary effluent such as 30/20 mg/l SS/BOD_5 quality, the commonly used tertiary processes such as filtration, microstraining, and land irrigation usually reduce further the finer suspended solids in the effluent and thus — fortuitously — also often reduce the oxygen demand. These processes do nothing to the dissolved non-bio-degradable substances which have already passed unaltered through the main treatment processes.

8.5.7. These dissolved non-bio-degradable substances can only be removed by what we call for this purpose advanced treatment processes which thereby come into their own. They are unique in this application which could well be of rapidly escalating importance, even if mainly in special circumstances.

8.6. — (f) Development

8.6.1. Dealing with the more promising processes first, coagulation, flocculation following the addition of lime, alum, or ferric salts enhances settlement and removes suspended solids well. A high dose also removes phosphate. Our work has shown potential for increasing the deposition of settleable solids by up to 50%, from a norm of about 50-60% without aids up to as much as 80-90% with aids. Phosphate removal may be more than 80% from about 50% to 90% and above. Some dissolved organic matter may be removed by precipitation. Adding coagulant chemicals does not normally affect the nitrate content of the effluent and only reduces ammonia when coupled with air stripping. This is especially interesting and applicable to situations where eutrophication is a problem. Lime reduces the temporary hardness of the wastewater but alum and ferric salts convert it to permanent hardness.

8.6.2. Activated carbon shows promise of removing residual suspended solids well, together with some dissolved organics. By careful selection the carbon structure can be tailored to remove specific substances by molecular incorporation. It has no effect on nitrates and ammonia and only removes phosphates when powdered and used with alum. Bacterial slime growing on the carbon grains may help the treatment process by removing more organic material but hinder its operation by blocking the carbon: it also generates offensive smells. The process is affected markedly by the yet unresolved economics and other aspects of regeneration. The carbon adsorbent stage is usefully preceded by multi-media filters to reduce at lower cost the quantity of solids passing to the comparatively expensive carbon stage. This lengthens the time between successive regenerations or replacement of the very costly carbon. Carbon adsorption has a special application for designed removal of particular groups of substances but at high cost over traditional treatment.

8.6.3. Dealing now with the more highly specialised and usually more costly processes which are likely to have limited application. Accepting a feed of say 30/20 mg/l SS/BOD standard, ultrafiltration removes suspended solids and dissolved organic matter well but not much else. Reverse osmosis removes suspended solids, dissolved organic matter, phosphates and other inorganic matter quite well, and nitrates and ammonia to some extent. These processes produce a high quality effluent but at high cost and their use for wastewater treatment is likely to be minimal for all but highly specialised industrial applications. Applications are mainly when the concentrate is more important than the effluent and when the effluent must be free of all organic residues.

8.6.4. Electrodialysis partly removes nitrates, ammonia, phosphates, and other inorganics and only when the suspended solids and dissolved organic material in the feed stock have been much reduced already by pre-treatment. It does not remove organic materials and thus is unlikely to be used for domestic wastewater treatment. It is expensive and energy-intensive. It can be applied when the residual organic matter is less important than the inorganic and need not be removed. It can also reduce the ionic content but non-selectively.

8.7. — (g) Possible future trend

8.7.1. In the United Kingdom the most usual wastewater to be treated at present is mainly of domestic origin with SS/BOD$_5$ values of about 350/350 mg/l. The most common effluent standards apply constraints only on suspended solids, and biochemical oxygen demand often to the normal 30/20 mg/l Royal Commission standard. Sometimes limits are imposed on ammonia. The traditional sequence of preliminary primary and secondary treatment stages is likely to continue to be widely used. When the receiving stream is likely to be used downstream for public supply a denitfication stage will probably often be added to the treatment plant. Traditional tertiary treatment will probably continue to meet most demands for higher then normal effluent standards but for constraints on suspensed solids, biochemical oxygen demand and ammonia only, as at present.

8.7.2. When something better is needed and other criteria apply, when particular noxious substances have to be removed, or when specific effluent qualities are required consistently, a chemical/physical stage will probably be incorporated to assist the retained mechanical, physical and biological stages.

8.7.3. When a traditional plant is overloaded, chemical aids to improve settlement may be used to improve the effluent and to defer structural extension in those cases when the plant can otherwise accept the higher flow satisfactorily. Lime is likely to be used extensively for this. Similarly chemical aids can be used to deal with shock or transient loads when these are foreseeable as for example from summer visitors to coastal resorts or visitors to festivals in inland towns. There is large scope for development of an automated 'clip-on' facility to provide this spasmodic aid.

8.7.4. When a traditional plant needs to provide an effluent of varying quality from a wastewater of constant strength (possibly seasonally or depending on flow or condition of the receiving water), or where a consistent effluent standard must be maintained with variable feed (possibly from shock or peak loads) the advanced treatment processes can help. They can provide the flexibility, control and predictable performance needed to supplement the main pollutant removal capability of the traditional plant and give treatment potential not otherwise achievable.

9. Conclusions

9.1. General Points

9.1.1. The pilot country concept pioneered by CCMS has helped us make a very usefully co-ordinated study of the AWT problem and enabled us to develop many promising associations for future work.

9.1.2. Our experience of the long study and the large resource investment has suggested that future studies of this type would gain from more precisely defined terms of reference.

9.1.3. We believe it important that the pilot country — and co-pilot countries to a lesser degree — should accept that adopting the role commits them to a lot of work.

9.1.4. In future similar studies we think a Technical Group should be set up immediately after appointment by the pilot country who should provide the Chairman and substantial administrative and secretarial support. The group should comprise named representatives from each participating country who would then act as the focal point and liaison officer for that country for the duration of the work.

9.1.5. An early meeting should draw up detailed objectives to implement the general aims of the project defined by CCMS including in particular a time limit both for the work and for the final report. Each country should say what contribution they propose to make to the study — accepting that later modifications may be made. These early decisions should be reported to CCMS to give them an appreciation of the work proposed.

9.1.6. The Technical Group should meet frequently — at least once before each CCMS Plenary Session and preferably in each of the participating countries in turn.

9.1.7. We found great benefit from expanding these progress meetings into general technical discussions within the subject area of the project. They should include visits to work in progress so that delegates can discuss the results informally and gain an understanding of the conditions in which they were obtained to help evaluate them. All delegates should aim to attend all meetings. The project staff, and others, would benefit from temporary attachment to contributory work in the various countries and interchange of staff generally would be an advantage.

9.1.8. Our work has shown the benefit of including within a single project a range of work from the laboratory bench through pilot scale to field scale so that final results can be used immediately and with confidence in operational practice. Limited and confirmatory pilot-scale work may then be necessary to evaluate local wastewaters and local conditions but nothing much more.

9.1.9. Dealing with this advanced wastewater treatment study in particular we think six years too long for a single project. We felt inhibited with terms of reference unchanged for so long and the consequent inflexibility was a real constraint. Whilst we have not yet solved all the problems set we think conditions in wastewater treatment generally have changed sufficiently to justify reviewing the original objectives. More meaningful progress might stem from encapsulating some future work into say two-three year project packages albeit each with more limited objectives but aggregating to a larger aim. Rapidly changing problems are best met by flexible response solutions.

9.2. Technical Points

9.2.1. The wide ranging and detailed work has led to a large number of minor technical conclusions which are set out in the main body of the report after describing the work from which they were drawn. They are not separately repeated now but in aggregation they support the following *broad conclusions on the likely application of advanced* treatment technology in general. As wastewaters inevitably become increasingly complex, each will merit separate consideration for treatment and thus general guidance is of limited value. Much more work must be done before detailed guidance can be given and the cost may need careful scrutiny in the light of the likely return.

9.2.2. The study has confirmed much of what we suspected to be true from previous smaller scale work on advanced treatment. Thus we can now advise more confidently in some areas and suggest more reliably where future work should be directed.

9.2.3. In the hypothetical 'normal' situation in the United Kingdom with mainly domestic wastes from an urbanised community, the straight 'PCT package' of chemically-aided settlement, filtration, and adsorption is unlikely to have overriding advantages over the conventional primary settlement and biochemical oxidation (including secondary settlement). This is particularly true when the effluent has only to comply with the traditional 30/20 mg/l SS/BOD$_5$ "Royal Commission Standard", or indeed to meet a modest denitrification requirement. Thus we think physical-chemical treatment unlikely to replace traditional treatment in the 'normal' case in the United Kingdom: however stages may be incorporated into combined treatment-chains as explained later.

9.2.4. We expect the traditional mechanical, physical, biological treatment chain to continue to provide the most effective and cheapest method for removing biodegradable pollutants from wastewater unless very special conditions apply either to the feed or to the effluent. Clearly the present low level technology and methodology can still be improved: first by developing the processes and equipment, secondly by improving the operation and management and thirdly by aiding it with chemicals and with higher technology.

9.2.5. When we need to deal with pollutants other than the easily removable non-biodegradable substances, the advanced treatment methods studied should be attractive and sometimes there may be no practicable alternative to them. In general they can provide a treatment capacity that can be matched to the load imposed and can be automatically controlled. They are reasonably resistant to shock loads, they often employ higher technology, they can be of advanced design and construction and can provide good working conditions.

9.2.6. But, most importantly, advanced treatment can be designed objectively to remove specific pollutants, to have predictable performance over a wide range and variable at will, and to be more reliably automated than traditional processes. Advanced treatment plants can be made more aesthetically attractive than traditional plants, although probably at some increase in cost.

9.2.7. In consequence advanced treatment is costly, requires skilled operation and management, and needs high technology support services but surely that is the price we must pay for the sophisticated treatment capability. We rarely get much for nothing in this materialistic world.

9.2.8. In the near future we envisage little application of physical-chemical processes alone for treating domestic wastewater. We may expect them to be used for treating some industrial wastewaters. Advanced methods may provide the only practicable solution for dealing with some wholly industrial effluents but those will be specific to local situations and requirements and not for general use. In summary traditional treatment will continue to be used to remove most biodegradable pollutants and to satisfy effluent requirements for suspended solids and biochemical oxygen demand. Advanced methods will be used when non biodegradable pollutants are a problem and the effluent needs to satisfy chemical requirements. A combination of traditional and advanced treatment is likely in many cases to treat both domestic and mixed domestic and industrial wastewaters.

9.2.9. Using oxygen in place of air in biological treatment may have special advantages in treating strong wastewaters containing industrial effluents and particularly those with a high carbohydrate content. We think the oxygen activated sludge process unlikely to replace the traditional air process for treating domestic wastes when the technical advantages may be finely balanced against the increased cost and the higher standard of operation and management needed.

9.2.10. Any method aimed at improving the solution of oxygen in wastewater merits study. We think the Deep Shaft may be promising when an effluent standard of 30/20 mg/l SS/BOD_5 is required but it is said to become even more attractive as the effluent requirements become less stringent. The cost is very dependent on good ground conditions for sinking the shaft.

10. Areas for future work

10.1. General Scope

10.1.1. Our Study has confirmed that the need for further work is virtually limitless if precise guidance is needed on the design, construction, operation, management and maintenance of advanced treatment plant for wastewaters. As the civilised world advances so does our knowledge and so do our demands. Achieving the very progress we seek may often generate its own new and unforeseen problems, many probably unforeseeable. Thus we can prudently only postulate general rather than specific areas for further work.

10.1.2. The Study has reminded us that we do not know with any great confidence or certainty the main health and other hazards likely from wastewater or from ineffective treatment of it. Presently we tend to devise protective measures before we know precisely what we are seeking protection from. We are developing solutions before defining the problems they may have to solve. We need to be more objective.

10.1.3. Our work has given us a feeling for both the technology and methodology of chemically aiding primary settlement and of using oxygen to improve the activated-sludge process. We think we now have sufficient information for drafting operational guidance but thought it outside the limits of the current project.

10.1.4. The Study has emphasised the need to establish and understand more clearly the effect of pollutants on the environment. We need to know how they originate, the way in which they are absorbed, deposited and accumulated. We need to know the mechanism of degradation and decay. This would lead to a better understanding of what pollutants (both occurring naturally and introduced artificially) should be removed, reduced or modified. It would then be necessary to devise specific methods of treatment and to decide at what point in the water cycle they should be applied.

10.1.5. The work has shown the need for and value of combining mechanical, chemical, physical and biological stages of treatment. Each of these stages is capable of further development and optimization singly and then more importantly we must identify the capabilities of combining them in various ways. This is a large task even on present knowledge of pollutants, a vast task when including other suspected hazards, and probably almost limitless if we are to deal with all likely future hazards. Clearly the priority of work will need to have regard to the seriousness with which the relevant hazard is viewed. We need to develop methods of designing plants with a specific treatment capability for selected pollutants derived from requirements in the field — a fundamentally new approach to replace present rule-of-thumb methods.

10.1.6. The Study has revealed a very urgent need for improved costing and especially methods of cost estimation. We need more reliable cost data, more comparative costs for evaluating options, and even more we need information on the much wider issues of process economics.

10.1.7. Our experience has convinced us that we shall need to train managers and operatives to handle advanced treatment processes and plants effectively. We think higher grade staff will be needed on advanced treatment plants than on traditional plants: they will need to be better educated, more highly skilled and specially trained for the new duties.

10.1.8. These general needs suggest the following specific areas for future study.

10.2. Specific Areas for Study

10.2.1. The first and major task is to identify the specific pollutants in wastewaters which are or may be significant hazards to health, the environment and amenity generally. It will be necessary to decide the tolerable concentrations in given circumstances. With the many present uncertainties we are not able to direct our current removal evaluations to other than the already known hazards and so our development is on general rather than on the specific lines we shall undoubtedly need in future.

10.2.2. The second task is to decide what environmental quality objectives are needed in various situations such as in re-use rivers, in drainage rivers, in recreational waters, in estuaries, and in coastal waters. Each country is likely to have its own particular requirements having regard to their use of the waters in question. The environmental quality objectives will lead to quality requirements for individual effluent discharges.

10.2.3. The third task is to develop optimized chains of both traditional and advanced treatment processes designed to remove specific pollutants predictably to meet various effluent standards. This development should cover all stages from the original concept to operating the plant in the field. The results should be codified in published guidance. The optimization should have regard to cost, energy consumption and other resource use as appropriate, and possibly to reducing significantly the quantity of sludge for disposal.

10.2.4. The fourth task is to develop methodology to evaluate the effect of the human contribution, the effect of quality of designer, constructor, operator and manager or the operational performance of the plant during the whole of its programmed life.

10.2.5. Developing these concepts leads to the following suggested projects.

10.3. Possible Projects

10.3.1. Publication of guidance on chemically-aided settlement of wastewater.

10.3.2. Optimization of the activated carbon use/regeneration cycle for a variety of pollutants and carbons and possibly for other adsorbents.

10.3.3. Evaluation of comparative process economics for traditional and advanced treatment processes for a range of pollutants.

10.3.4. Evaluation of methods of nitrification denitrification and ammonia removal having regard to the need to reduce the discharge of nitrates to the environment.

10.3.5. Evaluation of techniques for disposing of chemical sludges safely and economically.

10.3.6. Evaluation of the effect of operation and management and other skills on the continued performance of advanced treatment processes.

11. Draft resolution

11.1. The member nations of the Alliance do resolve:

a. To ensure a wide dissemination of the information contained in this report.
b. To pursue a fruitful exchange of information regarding advanced wastewater treatment.
c. To take account of the technical conclusions in the report for future application of advanced wastewater techniques.
d. To use their best efforts to implement the specific recommendations resulting from the experiences gained so far.
e. To take note of the suggestions for further work when planning future research.

12. Acknowledgements

12.1. The United Kingdom as Pilot Country acknowledges the considerable help received from its Co-Pilots and associates with gratitude. Neither the Report nor the Study would have been possible without the ready assistance given by our Partners. We cannot list all our helper by name — even if we knew them — nor indeed could we thank them individually and commensurately with their contributions. The United Kingdom is both grateful and proud to have had such splendid co-operation from all concerned.

13.

International AWT Group in June 1978

Mr R BEST United Kingdom Chairman
Mr R SURIYADASA United Kingdom Secretary

Dr R L BUNCH United States
Dr A S EIKUM Norway
Ministerialrat. Dipl. Ing. H MUEHLECK Federal Republic of Germany
Professor ING R PASSINO Italy
Dr P R PHILIP France
Dr J D SALLOUM Canada

Dr IR CJ DUYVERMAN TNO Netherlands (attended by invitation)

14. Definitions

14.1. The following describe in popular terms what we mean by key words in the Report which are usually given more scientific definitions.

14.2. ADVANCED WASTEWATER TREATMENT (AWT) has no universally accepted definition but we have interpreted it in this Study as any process — or combination of processes — not usually used at operational wastewater treatment plants.

14.3. BIOCHEMICAL OXYGEN DEMAND (BOD). The amount of dissolved oxygen consumed by microbiological action when a sample is incubated, usually for five days at 20°C. Unless otherwise stated the BOD referred to in the text is BOD_5.

14.4. BREAK-POINT CHLORINATION. The addition of chlorine to a water to the point where the free available residual chlorine increases in proportion to the incremental dose of chlorine being added.

14.5. CAPILLARY SUCTION TIME (CST). A measure of the filtrability of a sludge.

14.6. CAPITAL COST is the expenditure for which the benefit occurs over a long period of time.

14.7. CHEMICAL OXYGEN DEMAND (COD). The amount of oxygen consumed from a specified oxidising agent in the oxidation of matter present in a sample.

14.8. COST BENEFIT ANALYSIS (CBA) is the evaluation in monetary terms of all the consequences of a decision involving a comparison of the value in real terms (without any distortions) of benefits discounted to a base period with the value (also in real terms) of resources used to generate the benefits.

14.9. COST EFFECTIVENESS is either (i) Minimisation of the cost of resources used to achieve a given objective.
or (ii) Maximisation of output or service level with a given volume of resources.

14.10. DISCOUNTING is the reduction of the value of an item by a certain proportion related to the distance ahead of time.

14.11. DISSOLVED OXYGEN (DO). Oxygen dissolved in a liquid; the solubility depending on temperature, partial pressure and salinity.

14.12. EFFLUENT is the more liquid residue from wastewater treatment. It is usually subject to imposed discharge requirements.

14.13. GAS CHROMATOGRAPH MASS SPECTROMETER (GC/MS). A powerful analytical technique for the separation and identification of volatile organic substances; it is particularly well suited to the analysis of complex mixtures of organic compounds.

14.14. G R P is Glass Reinforced Plastic.

14.15. METHYLENE BLUE ACTIVE SUBSTANCES (MBAS) Used in tests to detect substances sensitive to methylene blue.

14.16. MIXED LIQUOR. A mixture of settled sewage and activated sludge undergoing circulation and aeration in the aeration tank or channel of an activated sludge plant.

14.17. MIXED LIQUOR SUSPENDED SOLIDS (MLSS). The concentration of dry solids of mixed liquor in the aeration tank or channels of an activated-sludge plant.

14.18. MOST PROBABLE NUMBER (MPN). A statistical estimate of the numbers of viable bacteria present in a sample.

14.19. N P K is Nitrogen, Phosphorus, Potassium.

14.20. OPERATING COST is the expenditure for which the benefit accrues immediately or over a short period of time.

14.21 PHYSICAL-CHEMICAL TREATMENT (PCT) comprises processes or groups of processes in which chemicals are added specifically to complement or enhance the performance.

14.22. REDOX POTENTIAL. A measure of the state of oxidation of a system.

14.23. SLUDGE is the more solid residue from wastewater treatment. It can be complex and is not always subject to disposal constraints.

14.24. SLUDGE VOLUME INDEX (SVI). A rough measure of sludge settleability.

14.25. STANDARD TEMPERATURE PRESSURE (STP). A temperature of 273.15 Kelvins and 101325 Pascals.

14.26. SUSPENDED SOLIDS (SS). Is the undissolved solids, mainly organic, contained in wastewater.

14.27 T O C is Total Organic Carbon.

14.28. TOTAL KJELDAHL NITROGEN (TKN). A measure of the total organic nitrogen.

14.29. TRADITIONAL TREATMENT comprises processes or groups of processes normally used in publicly owned and managed operational plants and usually includes mechanical, physical, and biological stages.

14.30. WASTEWATER flows from the water-carriage sewerage system in which water is used to carry human wastes in pipes which may also convey surface water and liquid industrial wastes. (Wastewater is often popularly called Sewage and described as the liquid waste of an urbanised community.)

14.31. WASTEWATER TREATMENT covers anything from removing some gross solids to producing a high quality effluent, possibly fit to drink. Normally it always involves separating solid from liquid and thus has more than one end product.